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Constrained Black Box Optimization for Radioisotope Thermal Generator Manufacturing

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Constrained Black Box Optimization for Radioisotope Thermal Generator Manufacturing

by

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Dedication

I dedicate this to my mom and dad.

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Abstract

Constrained Black Box Optimization for Radioisotope Thermal Generator Manufacturing

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This thesis aims to optimize the conditions and policies used at Los Alamos National Laboratory for the manufacturing of Radioisotope Thermal Generators used for deep space exploration. This manufacturing faces unique and stringent constraints on their operations as well as extraordinarily rigorous quality control measures to ensure that products will work when deployed. Furthermore, this manufacturing process is new, and no historical data exists to prove the capability of the manufacturing system and what the expected operating costs will be. Through this analysis, a theoretical model is constructed to understand the system dynamics to arrive at a theoretical product throughput.

A base case of the manufacturing system is created using values for the system as it is currently envisioned. From this case, the total cost, average total time per product, and the number of products completed are optimized. This optimization is achieved by changing the policies on how batches are formed and when operators should work to use resources most efficiently and ensure that no resource is under or over-utilized. It was

discovered that the most efficient policy is to add a half working day on Saturdays which significantly reduces the cost by about $700,000 when compared to having operators work 24/7. Furthermore, this policy can produce more products in less time than the case in which people work a standard shift Monday through Friday and decreases costs by about ~$30,000 utilizing the optimized values. Finally, using cost estimation techniques, the total manufacturing cost including fringe benefits, maintenance, operating supplies, and supervisory labor is estimated to be around $6,000 per product and total cost of $3M per year.

The results presented in this thesis can inform Los Alamos National Laboratory on the direction and policies that must be implemented to meet manufacturing targets. Furthermore, the methodology developed can be expanded and applied to other product lines throughout the lab to analyze throughput and stay cost efficient while meeting national security requirements.

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Introduction

Within the United States, manufacturing of national security-sensitive, transuranic actinide-bearing components and products is a capability unique to the Los Alamos National Laboratory (LANL). Manufacturing lines at LANL that work with these sensitive materials, notably the plutonium facility at TA-55, face unique and stringent constraints on their operations as well as extraordinarily rigorous quality control measures. As a critical part of the national security infrastructure, the plutonium facility operates under objectives that differ sharply from those employed in conventional manufacturing. This thesis aims to cost and optimize the resources that Los Alamos National Laboratory (LANL) currently has available to most efficiently meet the United States national security interests [1].

These interests have evolved since the end of the Cold War. In the early 1990s, both the U.S and Russia were left with thousands of weapons to maintain and safeguard, which is an expensive endeavor. Through a series of treaties, the number of strategic warheads has been vastly reduced by both parties but the cost to maintain these warheads persists. It is of interest, to both the U.S. and other nuclear powers, to further reduce the number of weapons to mitigate the high cost of maintaining and safeguarding these warheads. Under the 2001 Nuclear Posture Review, the U.S. adopted a new doctrine in which the strategic forces shift from being threat-based to a capability-based approach [2][3]. Through this shift, a New Triad emerged in which responsive infrastructure is needed to meet the capability approach doctrine.

With the closure of Rocky Flats, one of the largest nuclear weapons production facilities, in 1992 there was a need to transfer the production capability somewhere else to keep producing nuclear components. Los Alamos National Laboratory was tasked with acquiring this capacity and has been working steadily since then to perfect their manufacturing and production techniques. Since the 2001 Nuclear Posture Review, LANL has been trying to incorporate new modern manufacturing techniques to help meet the requirements of a “responsive infrastructure.” This condition means that LANL must be prepared at a moment’s notice to ramp up production significantly to either mass produce weapons or develop and certify new weapon systems in under 20 years [4].

Technical Area 55, the plutonium facility, is tasked with this endeavor of high precision-engineering of products for the country’s nuclear arsenal and space programs. Products manufactured here must meet the highest quality standards and degree of precision set by the National Nuclear Security Administration. However, to maintain product quality as production is ramped up, it is critical to understand the cost of each unit product to be able to correctly appropriate funds as more products are needed. Furthermore, it is also of importance to understand the physical limitations of the current manufacturing systems to predict throughput and mitigate chokepoints in the process to most efficiently utilize resources.

To arrive at this new responsive infrastructure readiness and capability, LANL is deploying modern manufacturing techniques in other non-critical product lines such that these methods can be tested and optimized before being implemented into any of the weapons programs. One of these non-critical product lines is the Radioisotope Thermal Generator (RTG) Heat Source program for the National Aeronautics and Space Administration (NASA). In this product line, a Manufacturing Execution System (MES) and Material Requirement Planning (MRP) system were implemented to meet 21st-century manufacturing requirements. However, this product must overcome challenges due to safety considerations in dealing with special nuclear material not encountered in other typical 21st-century manufacturing systems. This thesis will focus on this RTG Heat Source product line for analysis and optimization. First, a cost methodology is proposed to recognize the different drivers of total cost ranging from labor to fringe benefits. Next, a discrete event simulator is used to model the product line to understand the dynamics of the system to find the maximum theoretical throughput of RTGs per year. Finally, four case studies are presented on different alternatives LANL can pursue to meet their target demand each year while minimizing costs and maximizing resource utilization. Through this work, LANL can predict expenses for their different product lines and make changes necessary to stay cost efficient while meeting national security requirements.

Literature Review

RADIOISOTOPE THERMAL GENERATORS

RTGs have been critical to the United States exploration of outer space as they provide electrical and thermal power for the spacecraft and their scientific instrumentation [5] where conventional solar or chemical power generation is not practical or feasible [6]. As of 2010, the US has launched 45 RTGs on 26 different space systems ranging from navigation satellites to the New Horizons mission to Pluto [7]. NASA and the Department of Energy (DOE) recently developed the Multi-Mission Radioisotope Thermal Generator (MMRTG) which has a modular design to meet the needs of a wide range of missions [5]. This design consists of two major parts, a heat source and a thermocouple for electrical power generation.

Thermal Power Generation

Thermal power in an RTG is provided by a radioactive source which undergoes nuclear decay [8]. Eq. 1 gives the initial activity of the source, A_0, in Becquerels [9] [10].

$$A_0 = \lambda N_0 \qquad \textit{Eq. 1}$$

Where N_0 is the number of atoms at $t = 0$, and λ is the decay constant for the isotope which can be calculated by knowing the isotope's half-life, $T_{1/2}$ as shown in Eq. 2.

$$\lambda = \frac{\ln(2)}{T_{1/2}} \qquad \textit{Eq. 2}$$

The specific activity of the source can is then given in grams by dividing Eq. 1 by the weight in grams. Then, by multiplying the specific activity given by the energy, E, released per disintegration and assuming 1 MeV/s = 1.6021×10^{-13} watts then the specific thermal power given in watts per gram is shown in Eq. 3 [11].

$$\dot{P}_{th} = 1.6 \times 10^{-13} \frac{E\lambda A_v}{M} \qquad \textit{Eq. 3}$$

However, there are at least 1,300 radioactive isotopes available for selection of an RTG heat source. After down selecting isotopes with either long and short half-lives (i.e. 100 days < $T_{1/2}$ < 100 years), a minimum specific power of 0.1 watts_{th}/gram, and eliminating isotopes with powerful gamma-ray emissions, approximately 30 isotopes are left. Of these, only eight have desirable characteristics and are cost-effective [11]. For the MMRTG, NASA and DOE have selected ^{238}Pu as the heat source [5] with the given attributes in Table 1.

Characteristic	Units	Value
Half-life	Years	87
Type of Emission	-	Alpha
Activity	Curies/watt	30.73
Fuel Form	-	PuO_2
Melting Point	°C	2150
Specific Power	Watt/g	0.40
Power Density	Watt/cc	4.0
Radiation Levels		
Gamma Dose Rate	mR/hr @ 1 m	~5
Shield Thickness	cm	~0
Fast Neutron Flux	n/cm^{2}sec @ 1 m	260

Table 1: ^{238}Pu Characteristics [11] [12]

^{238}Pu was chosen for having a long half-life of 87 years with a high-power density and having low radiation levels since it is primarily an alpha emitter. Low radiation levels are desirable for limiting radiation exposures for personnel during production, fabrication, testing, and delivery [13] [14]. The MMRTG is rated to provide 2,00 watts of thermal power and 120 watts of electrical power, through energy conversion using thermoelectric materials [15].

Conversion to Electrical Power

RTGs generate electrical power by converting the heat released from the nuclear decay via thermoelectric converters [16]. Thermoelectric converters utilize a temperature difference between two dissimilar metals to produce a voltage difference [17]. This voltage differential is modeled by Eq. 4.

$$\Delta V = S\Delta T_{12} \qquad \textit{Eq. 4}$$

Where, ΔT_{12} is the temperature differential temperature and S is the Seebeck coefficient. To maximize the output voltage materials with high Seebeck coefficients or a large temperature differential is needed [18]. The MMRTG used in the 2011 mars surface mission utilized a PbTe thermoelectric material which achieved a 6.3% conversion efficiency from thermal to electrical power output [19].

DISCRETE EVENT SIMULATION

Discrete event simulation (DES) is a form of computer modeling that allows complex systems to be represented intuitively and flexibly. The term discrete indicates that the that the simulation moves forward in discrete time intervals and events are discrete [20]. A DES has six main components [21]:

1. **Entities**: these are the “pieces” that move through the system. Other entities can affect entities, they change states, and affect output performance measures. Entities

are created as they entered the system and destroyed when they leave. However, some entities can remain indefinitely in the system.

2. **Attributes**: These are characteristics that can be added to entities which can defer from entity to entity. Attributes are local variables for each entity which can include processing times and routings.
3. **Global Variables**: A type of variable that reflects characteristics of the system regardless of the number of entities. These global variables include work in progress (WIP), the number in the queue, and the simulation clock.
4. **Resources**: Entities compete for different resources which represent commodities such as employees and machines with a limited capacity. An entity seizes a resource and releases it when finished.
5. **Queues**: If a resource is taken, the entity must wait in line until the resource becomes available.
6. **Events**: This is something that occurs a time, t, which changes attributes or variables. Three types of events exist in DES: arrivals, departures, and destructions. Events are stored in the event calendar in chronological order.

These principal components together can be used to model anything from a single server queue to complex manufacturing systems [21].

Industry Case Studies

DES has been used in different fields ranging from call centers to hospitals to predict various performance metrics such as cost and max queue lengths. In [22] a PVC manufacturing plant was analyzed to show that throughput is directly related to waiting time, WIP, and resource utilization. It was discovered that performance was low due to a bottleneck of workers and machines not being utilized correctly.

In another case study [23], a machine shop floor for Kerala Electricals and Allied Engineering was analyzed. The purpose of this analysis was to show the current utilization of different machines in their base configuration and the throughput of parts. The system was then optimized to find the ideal floor configuration which minimized transfer times and added machines to mitigate bottlenecks. Similarly, in [24] a manufacturing system is modeled to identify and optimize resource reserves to find an optimal solution to meet increased demand in productivity. Finally, in [25] a small furniture manufacturing system is modeled to implement lean and green manufacturing concepts to reduce waste such as overproduction, human resources, transportation, inventory, motion, corrections, over-processing, and waiting. The study found an optimal work cell in the factory which reduced processing times.

Methodology

OVERVIEW

The RTG manufacturing process has been characterized by LANL in [26] such that operation steps durations, resources needed for each step, and failure probabilities are known. To quantify the costs associated with the manufacturing of RTGs, two methods exist: deterministic and stochastic cost modeling [27] [28] [29]. In deterministic modeling, the aim is to calculate the expected cost based on the process characteristics being well known, and they remain time invariant. Thus, the parameter values and initial conditions determine the output of the deterministic model. However, in this manufacturing process, there are dynamic processes that depend on each other, and each of these processes has associated uncertainties that make it change its behavior over time.

This RTG manufacturing process can be modeled using stochastic modeling [30] [31]. It is of interest to LANL to understand the costs associated with decisions that deviate from the standard process, in such a way that policies can be formed to meet internal targets. Furthermore, distributions on time taken to build each product based on these different strategies are of importance to calculate the theoretical throughput of the system. This methodology first describes the implementation of deterministic modeling to calculate total manufacturing costs. Secondly, a stochastic model is specified to find the time per product and the maximum throughput of this system. Finally, optimization is discussed in which the parameter space and objective function are defined with the aim of finding the optimal policy which balances costs, time in the system, and number of products produced.

DETERMINISTIC MODEL

To quantify the total manufacturing cost of the RTG assembly process one must do an in-depth economic analysis of the process starting from raw materials to shipping the product. The cost model is based on a hybrid bottom-up approach [32] [33] [34] [35] [36] where all the resources, such as labor force and machines, are identified. Once these resources are identified, associated costs and operating times of each resource are assigned based on available data. If data is not available, then a top-down approach is used to fill in missing information in the model. This type of hybrid model is data driven which requires gathering detailed data which sometimes is unavailable for various reasons, such as classification. However, missing data is estimated using top-down cost estimating, in which data from similar processes are used [34]. The following sections detail the structure of the deterministic cost model.

Simplified Manufacturing Process

The first task is to identify the resources used in the pit manufacturing program, a Process Flow Diagram (PFD) [26] was used to gather insight into the process. The PFD is very detailed in the order of operations and how materials (primary, waste, scraps) move through the process as well as the resources needed for each of the operations. A simplified version of the PFD is shown in Figure 1 from start to finish. The PFD shows major processes in rectangles and Quality Assurance (QA) decision checkpoints in diamonds. Furthermore, detailed information characterizing the time and the resources required per step is listed in Table 2.

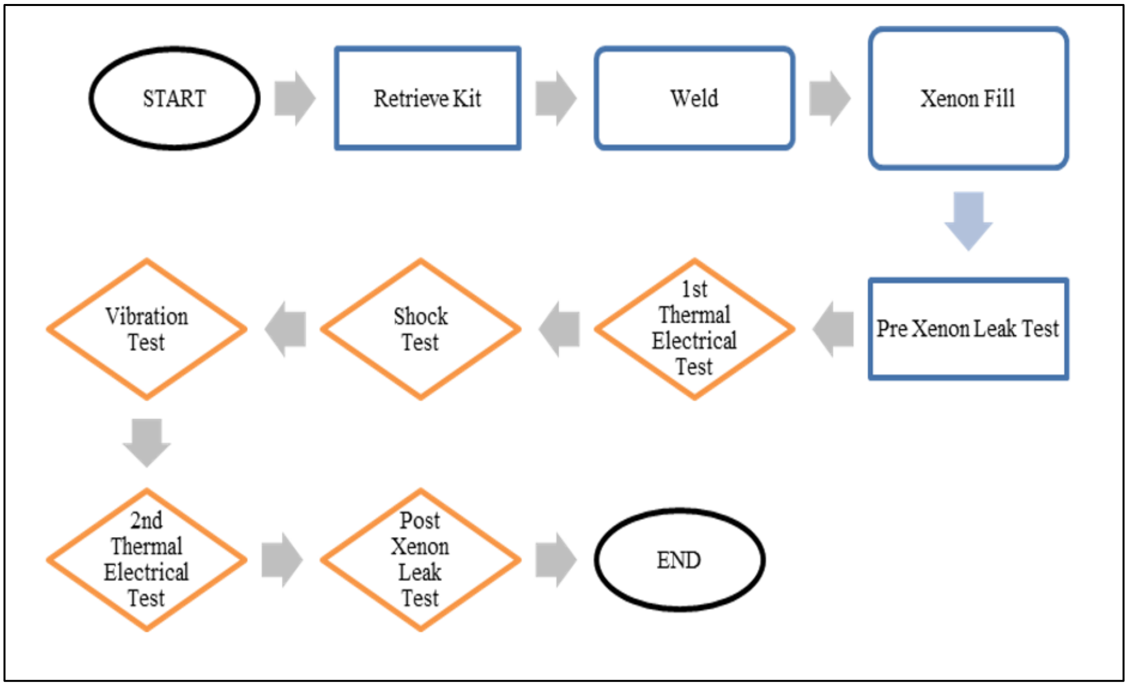


Figure 1: Simplified RTG Manufacturing Process Flow Diagram

Step	Description	Time (Hrs.)	Resources Needed	Resource Cost ($/hr.)	Failure Probability
1	Retrieve Kit	1.0	Operator (x2)	22	-
2	Weld	2.0	Operator (x2)	22	-
3	Xenon Fill	28	Operator (x2)	22	-
4	Pre-Xenon Leak Test	24	Operator (x2), Product Engineer	22, -	-
5	1st Thermal Electrical Test	32	Operator (x2), Product Engineer	22, -	15%
6	Shock Test	10	Operator (x2), Product Engineer	22, -	15%
7	Vibration Test	6	Operator (x2), Product Engineer	22, -	15%
8	2nd Electrical Test	32	Operator (x2), Product Engineer	22, -	15%
9	Post Xenon Leak Test	24	Operator (x2), Product Engineer	22, -	15%

Table 2: Simplified RTG Manufacturing Description by Step

The process is initiated by gathering the required parts and forming a "kit" which is then placed inside any of two assembly lines. Once the kits are inside the glovebox of either assembly line, they are assembled, and laser welded at which point they become RTGs. The RTGs are then backfilled with xenon gas and welded shut, and a leak test is performed as a baseline which is later compared to post xenon leak test.

The QA checkpoints happen at the end of the assembly process since the final product must be tested to ensure that it will maintain its mechanical structure and reliability after the rigorous stress testing procedures. In order, the tests are: first electrical test, shock test, vibration test, second electrical test, and post-xenon test. The electrical tests are done to test the performance of the electrical circuits under various temperature environments before and after mechanical tests. The shock and vibration tests are done to test the durability of the assembled kits under conditions they will experience when the RTGs are deployed for their missions. The post-xenon test is to check the level of xenon in the assembly against the baseline level measured previously to ensure that no leakage had occurred. At each testing stage, the assembled kits that fall below the testing thresholds are discarded, and only the heat source can be recovered.

Assumptions

The cost model, presented next, uses different engineering multipliers from the literature to give an entire picture of the cost. Using engineering multipliers is a common practice in cost estimation as seen in [37] [38] and [39]. These multipliers are presented here ensure that all the supporting costs are included without double counting.

- **Touch Labor**, is the labor directly involved with the production of the product such that the worker needs to touch the actual product to do an operation.

- **Technical Support Labor**, is the labor needed to support the production of the product such as RCTs that are involved in the process but do not necessarily come in direct contact with the product.
- **Sampling and Analysis Labor**, is the labor needed to test for quality control such as sending samples out of the production line to check chemical properties.
- **Direct Supervisory and Clerical Labor**, is the supervisory labor needed to keep the production line going (i.e. decision makers) and the clerical work to support the production such as data gathering. This multiplier is for personnel directly supervising the process such as the product engineer who makes decisions in the scheduling of machines to meet demand.
- **Operating Supplies**, are the miscellaneous supplies needed to keep the process functioning efficiently such as lubricants and chemicals, as distinct from major, itemized engineering material inputs.
- **Payroll Overhead**, this is more commonly known as "fringe benefits" which includes worker's compensation, pensions, insurance, paid vacations and holidays.
- **Administrative Costs**, these are expenses connected with top-management and regulatory activities. This multiplier defers from the Direct Supervisory and Clerical Labor multiplier in that this multiplier is specific to top management (i.e. lab director) and to run the laboratory, which has little to do with the product.
- **Maintenance Cost**, expenses associated with preventative maintenance to keep the manufacturing process running with little to no downtime for damaged machines.

Another multiplier is a special requirement and high precision multiplier, $M_{SRHP.}$, which is used to account for added complexity and process special requirements which end up adding extra time to the overall manufacturing process. This multiplier is used in this process to account for special requirements such as having to log data into the Manufacturing Execution System (MES) to ensure that the final product can be sold. Another special requirement which significantly adds time is having to work in a moisture free environment. Having to move RTGs and tools in and out of the gloveboxes requires time as they must first be decontaminated, which is not captured in the PFD for this process.

Special Requirements and High Precision Multiplier

This multiplier is derived from a similar multiplier in the literature which considers high precision operations. To quantify the relative cost difference between the standard process and the special process, Figure 2 is used. The relationships to form this multiplier where obtained from [40]. This multiplier is generalized to the unique and challenging manufacturing requirements in LANL. However, the exact precision is not known since the challenges at LANL go beyond attaining higher precision. Thus, this multiplier is used as a calibration factor to find an "effective precision" which for simplicity scales the times for each operation.

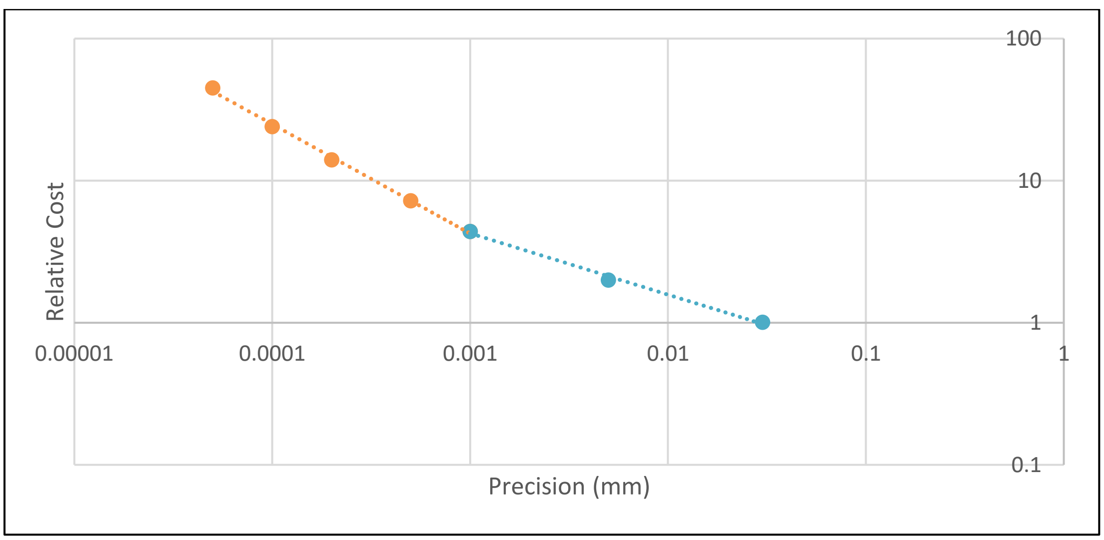


Figure 2: Precision vs. Relative Cost

Cost Estimation

The unit cost for this manufacturing process can be derived from an influence diagram which visually depicts key elements such as decisions, variables, and an objective, as seen in Figure 3. The influence diagram has four major parts to it: touch labor, non-touch labor, plant overhead, and fixed costs. For this process, the fixed costs are not considered as they have no bearing on decision-making for this operation [41]. However, to present a complete methodology (for implementation in other product lines) the fixed cost category is kept but not used. The first three components constitute the variable cost of the process. The total unit cost (UC) can be determined by adding the variable and fixed costs as seen in Eq. 5 given in units of \$/RTG.

$$UC = VC + FC \qquad \text{Eq. 5}$$

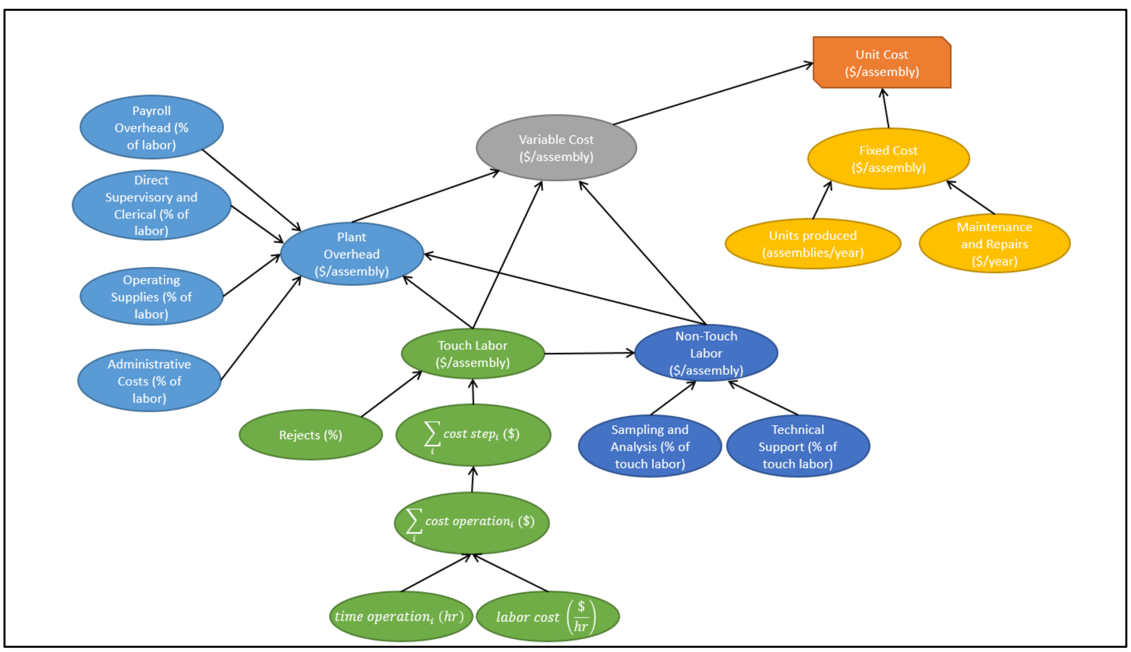


Figure 3: Cost Estimation Influence Diagram

Touch Labor Costs

Touch labor is the labor required directly by the manufacturing process in such a way that workers are directly touching the parts by doing different operations to manufacture them. This cost is modeled using Eq. 6.

$$TLC = \sum_j TLC_j = \sum_i \sum_k (LT_{i,j,k} \times ULC_k) \qquad \text{Eq. 6}$$

In such a way that the total Touch Labor Cost (TLC) from start to finish is the sum of TLC_j [$/RTG] at every step. TLC_j is calculated at each step j as a function of labor time ($LT_{i,j,k}$) in hours for class k, in step j, and in operation i and the unit labor rate cost (ULC_k) for class k in units of $/hour.

Non-Touch Labor Cost

Non-touch labor is the labor required in the backend of the process, but it does not necessarily interact directly with the assembly process such as sending samples out for testing. Another example is the technical support to the assembly process such as having a radiological control technician (RCT) check for contamination at different points in the process. This cost can be quantified using Eq. 7.

$$NTLC = SALC + TSL \qquad \text{Eq. 7}$$

Where, NTLC is the Non-Touch Labor Cost [$/RTG] which is the sum of the Sampling and Analysis Labor Cost ($SALC$) and the Technical Support Labor Cost ($TSLC$). $SALC$ and $TSLC$ can be quantified using Eq. 8 and Eq. 9.

$$SALC = TLC \times M_{SAL} \qquad \text{Eq. 8}$$

$$TSLC = TLC \times M_{TSL} \qquad \text{Eq. 9}$$

Such that $SALC$ [$/RTG] and $TSLC$ are functions of TLC and their respective multipliers. M_{SAL} is a multiplier to account for labor incurred for sampling and analysis and M_{TSL} is a multiplier to account for technical support labor, both are found in engineering estimate literature [37] [38] [39].

Plant Overhead

For any business, there is always overhead costs associated with it that must be incurred to keep everything running smoothly from clerical services to supervisors. This cost can be modeled by first quantifying the value that this other personnel is adding to the overall process as seen in Eq. 10.

$$DSCLC = (TLC + NTLC) \times M_{DSCL} \qquad \text{Eq. 10}$$

In which TLC and NTLC are summed together and multiplied by M_{DSCL}, a multiplier from the literature to account for direct supervision of the product, to yield a direct supervisory and clerical labor cost ($DSCLC$) in units of $/RTG. Then, all the labor including personnel not directly involved with the product is given by Eq. 11 where all labor costs (ALC) is the sum of TLC, NTLC, and DSCLC and has units of $/RTG.

$$ALC = TLC + NTLC + DSCLC \qquad \text{Eq. 11}$$

Once this is calculated, the payroll overhead (PO) is determined by multiplying ALC by M_{PO} which is a multiplier from the literature to account for the fringe benefits of anyone working with the product either directly or indirectly as shown in Eq. 12, given in units of $/RTG.

$$PO = ALC \times M_{PO} \qquad \text{Eq. 12}$$

Similarly, administrative costs (AC) is calculated by multiplying ALC by M_{Admin}, a multiplier from the literature to account for upper management involved with the product line as seen in Eq. 13.

$$AC = ALC \times M_{Admin} \qquad \text{Eq. 13}$$

Furthermore, to keep the product line running optimally there are materials needed to support the line such as cleaning supplies and tool replacements that add to the total cost. These operating supplies cost (OSC) in $/RTG are given by Eq. 14.

$$OSC = (TLC + NTLC) \times M_{OS} \qquad \text{Eq. 14}$$

In which, the TLC and $NTLC$ are multiplied by M_{OS} a multiplier from the literature to account for the supplies needed during operation to build the product, which is not the same as raw materials. It should be noted that OSC only accounts for labor directly associated with the product and not clerical supplies since these are already lumped into other multipliers [37]. The total overhead cost (OC) is then given by adding all the different overhead components as seen in Eq. 15 and is in units of $/RTG.

$$OC = PO + DSCLC + OS + AC \qquad \text{Eq. 15}$$

Fixed Costs

It should be noted that up to now all the costs are variable and directly depend on the number of units produced each year. However, there are other costs that the process accrues whether it is building one unit or a hundred units. For this manufacturing system, the fixed costs are determined by Eq. 16 in which only the yearly maintenance cost (MC_{yr}) is of importance and is given in units of $/yr.

$$MC_{yr} = CC \times M_{YM} \qquad \text{Eq. 16}$$

This cost is calculated by multiplying the capital cost (CC) of the major equipment in the process by a M_{YM}, a multiplier from the literature [39] to account for yearly maintenance of machines involved in the process. However, since the model calculates the cost in a per unit basis, Eq. 17 is modified to yield a maintenance per unit (MPU) cost as seen in Eq. 17, where Eq. 16 is divided by UP_{yr}, the number of units produced for the representative year.

$$MPU = \frac{MC_{yr}}{UP_{yr}} \qquad \text{Eq. 17}$$

Reject Modeling

The manufacturing system is not perfect, and defects occur at different stages which cause the RTG to be rejected. When an RTG is rejected, it is assumed that none of the components can be salvaged and all the labor costs up to the failure point are still accounted for in the cost. At a QA test, the product can either pass or fail, however, if it fails the QA engineer can decide to retest the product, send it back to a previous step, or simply reject it. If a re-test occurs, that implies that the step (the test) must be done again which adds to the total cost, this is done if there is a suspicion that the test was a false-positive. However, a test which sends the RTG to a previous step signifies re-doing some operations to get the

RTG to an acceptable level to pass the QA test. It should be noted that probability of failing a retest is not equal to the probability of a new part failing the test for the first time. Due to information on retesting not being readily available, the model gives the same failure probability to tests and retests [41]. Figure 4 and Figure 5 show the two type of outcomes that can occur in this system. After each step, the product can fail with probability P_{fail} or pass with probability $P_{pass} = 1 - P_{fail}$.

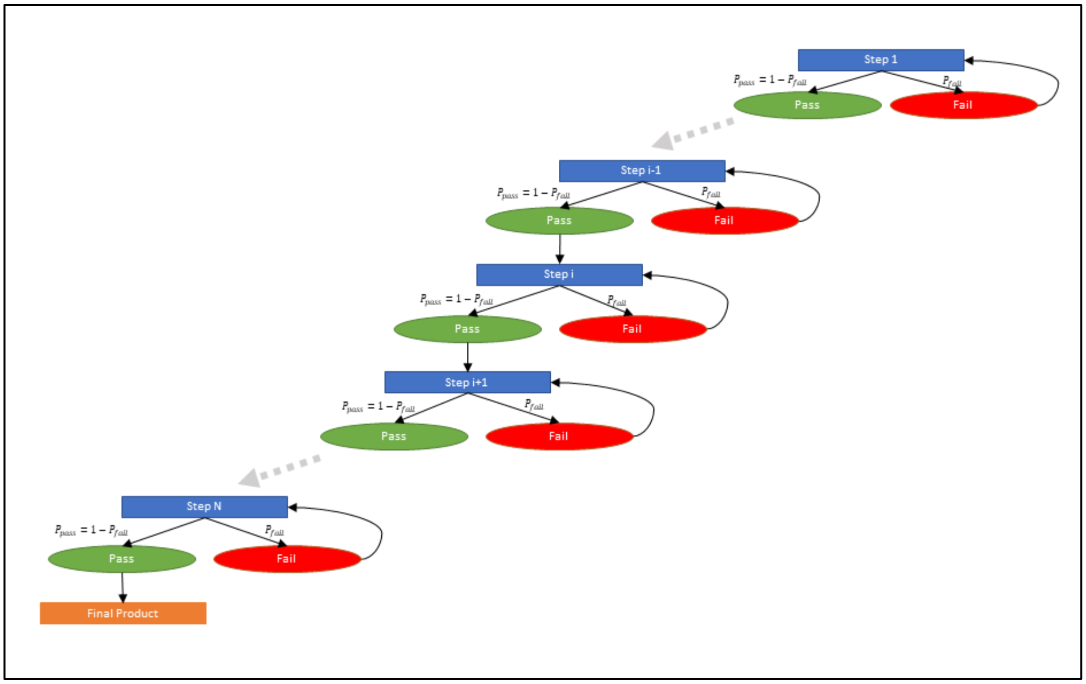


Figure 4: Failure Modeling: Redo Step

In Figure 4, RTGs that fail a QA test can go back one step to try to redo the failed operation, and then they are retested. This scenario adds cost to repeating the previous step and doing the test again. In Figure 5, RTGs that fail are scrapped and sent to the beginning to repeat all the steps.

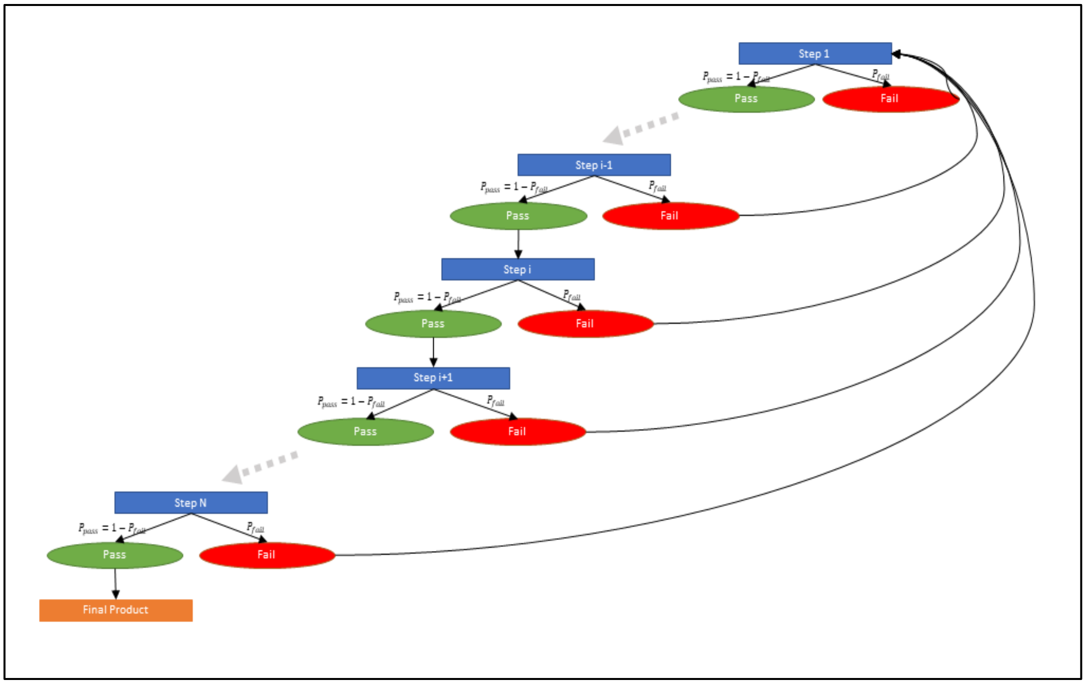


Figure 5: Failure Modeling: Restart from Beginning

The rejection cost (RC) from these failures can be mathematically modeled by Eq. 18 in which it multiplies the cost of all previous steps up to step i with the probability product of failing the current step. The failure probability product is obtained at each step, N, where the last step is defined as being $N = 1$, i is the current step, and k is the number of steps back. For this system, k is chosen such that $k = 1$ for the case in which the test is done again and $k = 5$ in the case that the RTG is completely scrapped. This formulation is flexible enough to allow the process to go back any number of steps if the process was modified to were parts can be reworked instead of just tossing the failed parts away.

$$RC = \left(\sum_{l=1}^{i} TLC_l\right) \times \left(\prod_{j=\max(i-k,1)}^{N+1-i} \frac{1}{(1-p_j)}\right) \qquad \text{Eq. 18}$$

Key Input Base Values for Deterministic Cost Model

Figure 6 shows the base values for different key inputs and multipliers needed to calculate the cost in $/RTG and $/year for the manufacturing process.

Input Table			
Parameters	Units	Input	Source
Manufacturing Engineering Multipliers			
Technical Support Labor	% of TLC	**60%**	Literature: Anderson
Direct Supervisory and Clerical	% of TLC and NTLC	**25%**	Literature: Peters
Utilities	%	**20%**	Literature: Peters
Operating Supplies	% of TLC and NTLC	**30%**	Literature: Anderson
Sampling and Analysis Labor	% of TLC	**20%**	Literature: Peters
Payroll Overhead	% of ALC	**40%**	Literature: Humphreys
Administrative	% of ALC	**15%**	Literature: Peters
Capital Investment Multipliers			
Other Multipliers			
Verification	% of time	**30%**	Assumed
Training	% of time	**30%**	Assumed
Generic Precision Measure	mm	**5.00E-05**	Scaling
Process Special Requirements and Precision Multiplier	%	4263%	
Rejection			
Major Checkpoints	-	**5**	Report Appendices
Average Rejection Rate	%	**15%**	Assumed
Rejection Rate Step 1	%	**15%**	Assumed
Rejection Rate Step 2	%	**15%**	Assumed
Rejection Rate Step 3	%	**15%**	Assumed
Rejection Rate Step 4	%	**15%**	Assumed
Rejection Rate Step 5	%	**15%**	Assumed
Pay Rates			
Operator	$/hr	**$22.00**	Payscale

Figure 6: Base Values for Deterministic Model

DISCRETE EVENT MODEL

The deterministic model, previously presented, calculates the cost without adding interactions between the different processes and the product such as a product going through a retesting procedure after failing a test or a machine breaking halfway through a test. Thus, a discrete event model that keeps track of every event in the system is needed to understand the dynamics of the system over time.

Model Structure

The manufacturing process is divided into two major sections: 1) RTG assembly and 2) RTG testing, with each of the sections having a more detailed granularity of what occurs at each step. This process is modeled in Arena using the structure shown in Figure 7. The model begins by having the kits diverted into either Assembly A or Assembly B, further detailed in Figure 8.

The processes are almost identical to one presented in the Simplified Manufacturing Process section. However, the Arena model contains more detail wherein the simplified model; some processes were lumped together for simplicity. The assembly sub model begins by having an operator retrieve kits (including heat sources). Once the kits are in the glovebox, the equipment and power are checked for each kit to ensure that tools needed for assembly are already in the glovebox and that there are no power spikes or surges keeping the laser welder from functioning correctly. The kits are stacked together in their final configuration, at which point it is verified that all the components are there. Once the verification is complete, the assembly is laser welded together followed by a visual inspection of the weld. At this point, the "kit" changes to be an "RTG." Before beginning the quality assurance tests, the RTG is backfilled with xenon which will be used for testing leaks within the RTG. The testing procedures are the same as in the simplified model.

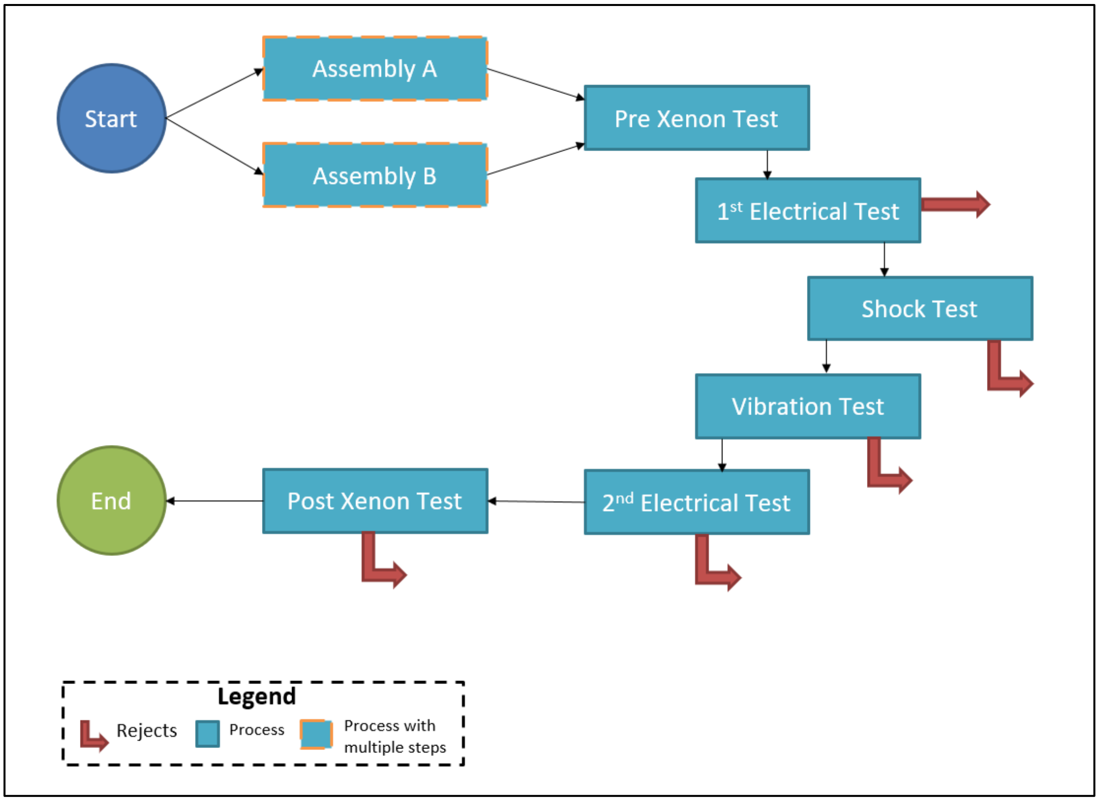


Figure 7: Arena Model Structure

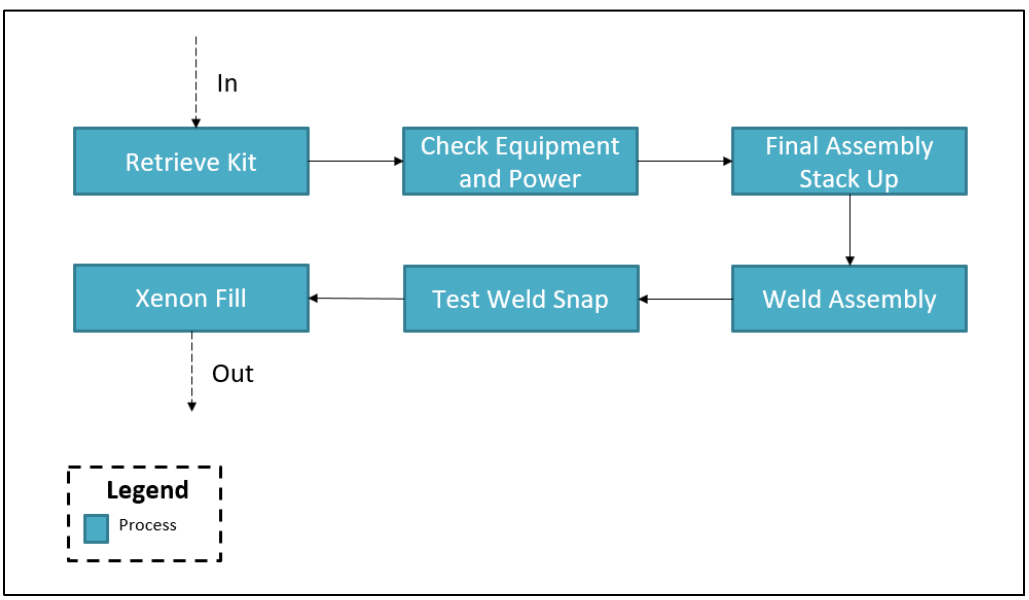


Figure 8: Arena Assembly SubModel

Arrivals

Arrivals of kits into the system are dependent on having enough inventory on hand for building the RTG and having heat sources to power the RTG. It is assumed that there is always enough inventory on hand and that the arrival is therefore driven by having heat sources available. The heat sources are produced in Plutonium Facility 4 (PF-4) within LANL which is independent of the PF-5 manufacturing facility in such a way that heat source manufacturing is agnostic to the demand of RTGs in PF-5. The arrivals of kits into the system can be modeled using a Poisson process [42] [43] [44] [45].Without further information, it is appropriate to assume that the interarrival times are exponentially distributed [46]. A relationship between the two is that the Poisson provides an appropriate description of the number of occurrences in a time interval, while the exponential describes the amount of time between events [47]. The exponential distribution has a memoryless property which allows it to have independent interarrivals without caring about arrivals at other time intervals with an expected value [48] described by Eq. 19.

$$E\left[\lambda e^{-\lambda x}\right] = \frac{1}{\lambda} \qquad \text{Eq. 19}$$

The expected value only depends on lambda, the mean time between interarrivals. For RTG manufacturing it is assumed that the mean time between kits arriving is two weeks [26].

Assembly Stage Assumptions

Once the kits have arrived at the system, they enter a queue where they are batched together. Each batch is routed into either assembly line A or B. Once a batch enters an assembly line it must remain there until the RTG is fully assembled. Line A and B are identical and independent of each other, for example, if Line A goes down, the products from Line A cannot be moved to Line B.

The assembly steps and their respective times are shown in Table 3. The nominal values were obtained from [41] assuming a Gaussian distribution with a variance of 5% of the nominal value.

Step	Time (Hours)
Determine Heat Source	NORM (0 .5 ,0.05)
Retrieve Heat Source	NORM (0 .5, 0.05)
Check Equipment and Power	NORM (0 .5, 0.05)
Final Assembly Stack Up	NORM (0 .5, 0.05)
Weld the Assembly	NORM (0 .5, 0.05)
Test Weld Snap Plates and Perform Visual Inspection	NORM (0 .5, 0.05)
Xenon Fill	NORM (28, 2.8)

Table 3: Assembly Stage Nominal Values

Testing Stage Assumptions

Once the kits have been assembled into RTGs, they undergo different test shown in Table 4. The nominal values were obtained from [41] assuming a Gaussian distribution with a variance of 5% of the nominal value.

Step	Time (Hours)
Pre and Post Xenon Leak Test	NORM (24,2.4)
Electrical Tests	NORM (32, 3.2)
Shock Test	NORM (10 ,1)
Vibration Test	NORM (6, 0.6)

Table 4: Testing Time Assumptions

Batch Size Assumption

As the kits or RTGs move through the system, they move together in batches due to physical or environmental restrictions. During the assembly process the kits are batched together and moved into the glovebox, then the glovebox is closed, and a moisture free atmosphere is created. In such a way that no other kits can be introduced into the glovebox until the current batch is finished. It should be noted that each glovebox has a limit of 8 kits or RTGs for safety purposes [26]. For the testing procedures, the batch sizes are dictated by the number of physical slots located in each testing machine. Table 5 below gives the assumptions for batch sizes for the different steps with a base, minimum, and maximum value for each batch.

Batch Name	Units	Base	Min	Max
Assembly	Kits	4	1	8
Pre and Post Xenon Leak Test	RTGs	12	1	12
Electrical Tests	RTGs	4	1	4
Shock Test	RTGs	2	1	2
Vibration Test	RTGs	4	1	4

Table 5: Batch Size Assumptions

Resource Assumptions

During this manufacturing process, different resources must be used to transform kits into RTGs and to conduct quality tests. The resources are divided into either human or machine resources. In this model, the human resources are made up by the operators who are in direct contact with the products. Table 6 below shows the different resources in the model with their respective capacities, hourly rates, and usage costs.

Resource Name	Units	Base Cap.	Min Cap.	Max Cap.	Hr. Rate ($/hr.)	Usage Cost ($)
Line A	Batches	3	1	8	-	-
Line B	Batches	3	1	8	-	-
Box A1	Batches	1	1	1	-	-
Box A2	Batches	1	1	1	-	-
Box A3	Batches	1	1	1	-	-
Box B1	Batches	1	1	1	-	-
Box B2	Batches	1	1	1	-	-
Box B3	Batches	1	1	1	-	-
Operator	People	6	1	15	22	-
Xenon Backfill Chamber A	Batches	1	1	1	-	4600
Xenon Backfill Chamber B	Batches	1	1	1	-	4600
Mass Spec	Batches	12	12	12	-	-
Thermal Chamber	Batches	4	4	4	-	-
Shock Tower	Batches	2	2	2	-	-
Vibration Table	Batches	1	1	1	-	-

Table 6: Resource Assumptions

It should be noted that the batch size and resource capacity are not the same things. The resource capacity is not a choice in the system but rather the processing capability, i.e., the capacity given is the number of batches that each resource can handle. The base capacity is the same as the maximum and minimum capacity for each of the machine resources. This capacity limitation is by design since no new machines can be added to the system due to floor space limitations. However, the operator resource can be varied as human resources can be added or removed from the system. The operators have an hourly cost of $22 per hour whether they are idle or busy. For this model, only the xenon backfill has a usage cost associated with it due to the high price of xenon gas [personal communication]. It is assumed that the usage cost each time this resource is used is ~$4,600. This was calculated by assuming that a box with a volume of $(1.0)^3$ cubed meters is filled with xenon gas for backfilling the RTGs. The cost of xenon is assumed to be $850/kg [49] [50] and the density of xenon is 5.472 kg/m^3 [51].

Number of Kits per Arrival

Currently, there is no previous historical data on the throughput rate of heat sources from PF-4 to PF-5. Therefore, a sensitivity analysis was done to quantify the maximum theoretical throughput of RTGs out of PF-5 which can be used to "create" a demand of heat sources out of PF-4. This sensitivity analysis assumes that the system is at its base values and that there are operators working around the clock 24/7 to ensure that kits and RTGs are moving as soon as they finish each step.

The results for this sensitivity are seen in Figure 9 where the blue data points represent the number of completed RTGs out of the system, and the orange data points are the number of RTGs and kits left in the system after the simulation is finished. To obtain useful statistics and tight half width intervals, 200 replications of each simulation were done [21]. Error bars were omitted as the error was low as compared to the output, in which the bars were smaller than the data points shown in Figure 9. It is seen that the number of completed RTGs reaches an asymptote of ~880 RTGs even if the number of kits per arrival continues to increase. Thus, it is seen that as the number of kits per arrival increases the number of kits/RTGs left in the system increases significantly.

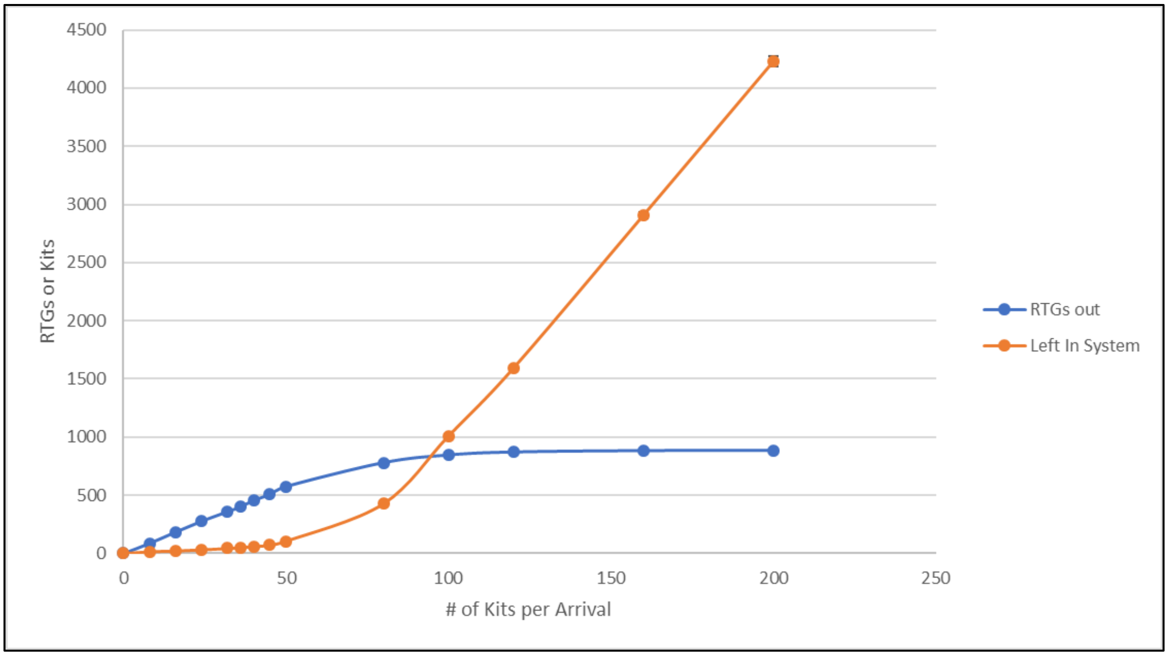


Figure 9: Sensitivity to Number of Kits per Arrival

Both datasets can be described by polynomial fits: the completed RTGs is best represented by a third order polynomial, as seen in Eq. 20 and the kits/RTGs left in the system can be modeled by a second order polynomial as seen in Eq. 21.

$$C\ = 0.0001x^3 - 0.0784x^2 + 15.19x - 29.2 \qquad \text{Eq. 20}$$

$$L = 0.118x^2 - 1.6691x - 28.577 \qquad \text{Eq. 21}$$

Where C is the number of completed RTGs and L is the number of kits/RTGs left in the system. Both are functions of the number of kits per arrival, x. It is seen that these curves intersect at x ≈ 90 kits per arrival, after this point the number of kits/RTGs left in the system exceeds the number completed RTGs, in this study arrivals will not exceed this tipping point. However, a number of kits per arrivals close to this point is chosen to “stress” the system to try to utilize its resources as often as possible, rather than having resources be idle waiting for more kits to arrive. For this study, 80 kits per arrival was chosen as the nominal value for the model.

Design Space Variables

In trying to optimize there are limitations on what can be changed on the system. For example, adding new machines is unfeasible as there are space constraints. However, there are different decisions that can be made that will significantly vary the dynamics of the system. The decisions that can be made are mainly for personnel capacity, personnel schedules, and batch sizes at different points. These variables are shown in Table 7, with the nominal value at its current state and the upper and lower bounds for that variable.

Variable	Units	Base	Min	Max
numTechs	People	6	2	15
assemblyBatch	Kits	4	1	8
xenonBatch	RTGs	12	1	12
electricalBatch	RTGs	4	1	4
shockBatch	RTGs	2	1	2
vibrationBatch	RTGs	4	1	4
Line A	Batches	3	1	8
Line B	Batches	3	1	8

Table 7: Design Space Variables

Objective Function

The goal of using the discrete event simulator is to find an optimal configuration of variables that will minimize the objective function. For this process, a weighted sum is used with equal weights for each objective. It is a choice at LANL what weights must be used to meet their specific needs. The objective function consists of three objectives: 1) minimize time per unit, 2) minimize overall cost, and 3) reward. To minimize the time per unit the system must inherently minimize non-value-added time such as waiting in queues to get processed. Furthermore, the overall cost is dictated by personnel costs and the cost of running tests. It is assumed that the test cost is fixed and does not depend on the number of units being tested. Mathematically, Eq. 22 expresses the objective function mathematically.

$$\min z = w_1 \times \frac{UT}{UT_{norm}} + w_2 \times \frac{Cost}{Cost_{norm}} - w_3 \begin{cases} \frac{Penalty}{Reward_{norm}} & N_{RTG} < T \\ 0 & N_{RTG} = T \\ \frac{Reward}{Reward_{norm}} & N_{RTG} > T \end{cases} \qquad \text{Eq. 22}$$

Where w_1, w_2 and w_3 are chosen to be equal and sum to unity, i.e. $w_1 = w_2 = w_3 = \frac{1}{3}$, and have no units, but will be refined by LANL based on their needs. The time per unit is defined by UT and Cost if the total cost after one year of simulation. These two objectives are normalized by the value achieved in the base case. The objective function has a reward function for meeting a production target. For example, if the simulation does not achieve a target, T, number of complete RTGs at the end of the simulation, the objective function will be penalized making it an undesirable solution. Three reward scenarios can happen: 1) the number of RTGs is below the target resulting in a penalty, 2) the number of RTGs is equal to the target for which case there is no reward or penalty, and 3) the number of RTGs is above the target resulting in a reward.

System Constraints

For safety concerns and space limitations within each assembly line, the number of kits per line cannot exceed 24 units [9]. Therefore, the following constraints are applied to the optimization to ensure that this does not occur when searching for the optimal solutions.

$$assemblyBatch \times Line\ A \leq 24 \qquad \text{Eq. 23}$$

$$assemblyBatch \times Line\ B \leq 24 \qquad \text{Eq. 24}$$

Optimization

Arena has a built-in optimizer, OptQuest, which uses a Scatter Search also known as Tabu Search algorithm to find optimal solutions [52] [53]. This method belongs to the family of evolutionary algorithms in it maintain a population of solutions and combines these solutions to obtain new solutions. This type of optimization works well with black box models. However, the initial population aims cover the variable search space by sub diving the space into bins and sampling out of these bins. The algorithm consists of six methods as shown in Figure 10: 1) initial scatter set of diverse solutions is created by spanning the variable space, 2) initial scatter population is ranked, and a reference set is created by taking the top and diverse solutions, 3) create candidate by combining reference set, 4) bad solutions are replaced by better candidates, 5) local search is conducted to accelerate convergence, and 6) the reference set is randomized to avoid getting stuck in a specific region [54].

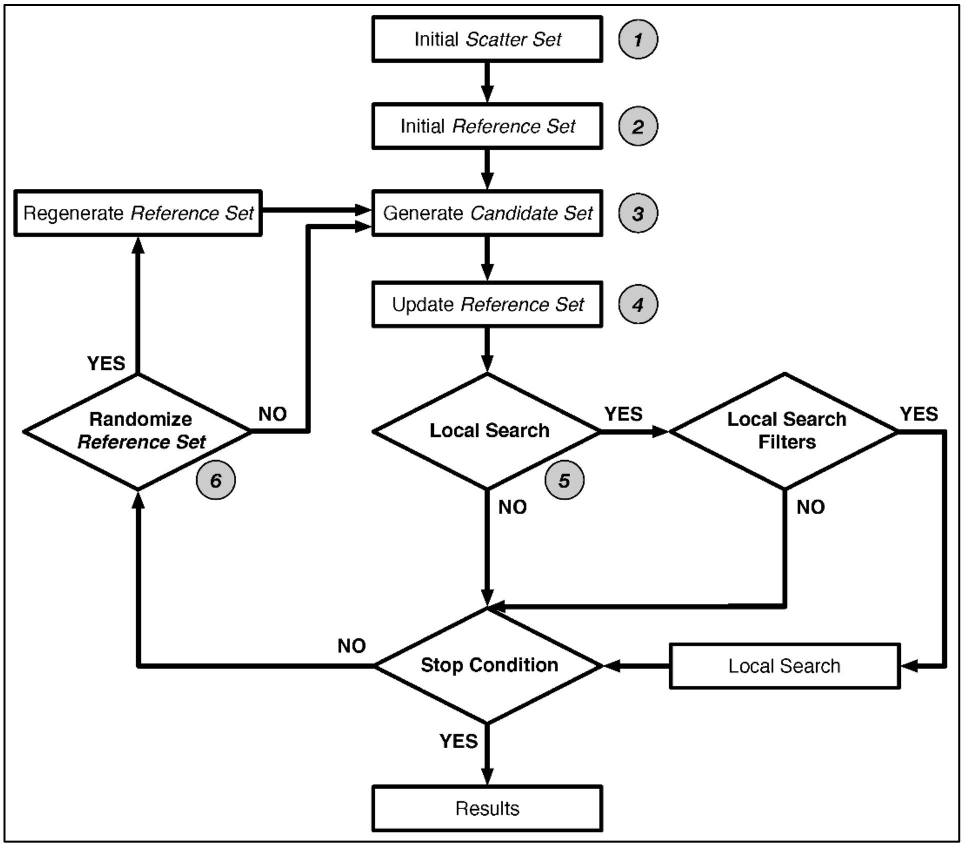


Figure 10: Scatter Search Algorithm [54]

CASE SCENARIOS

Different case scenarios are presented to illustrate the types of policies that LANL can implement to meet their targets.

- **Base Case:** Shows the current capability of the system as it currently stands in which operators work Monday through Friday from 7 AM to 5 PM with a one-hour lunch in between.
- **1.5 Shifts:** Adds an extra half working day on Saturday morning from 7 AM to 12 PM. Assumes that the same operators who work during the week also work this extra day.

- **2 Full Shifts:** Adds a new set of operators who work a full shift at night. There is a two-hour lag between shifts in which there are no operators present to continue operations such. In this case, operators are working 18 hours a day.
- **Machines Fail:** Assumes that preventive maintenance is not done, and the machines will start to fail as time progresses. The machine will only be fixed after it has failed. It is assumed that the time, in days, until a machine fails follows an exponential distribution ~EXP (12) and that the downtime in hours is also normal ~NORM (48, 4.8). More information on the choice for an exponential distribution is detailed in the results section.

Results

The following sections discuss the results from the scenarios described previously and insights found with choosing different policies. The cases are compared to the "ideal" case in which operators are available 24/7, in which case kits/RTGs move from station to station seamlessly without having to wait for operators to be available. In this idealized case, the system can produce 779 ± 18 completed RTGs with an average total time of 1023 ± 52 hours at a total resource cost of $1,579,161. However, the operator spends most almost half the time in an idle state as shown in Figure 11.

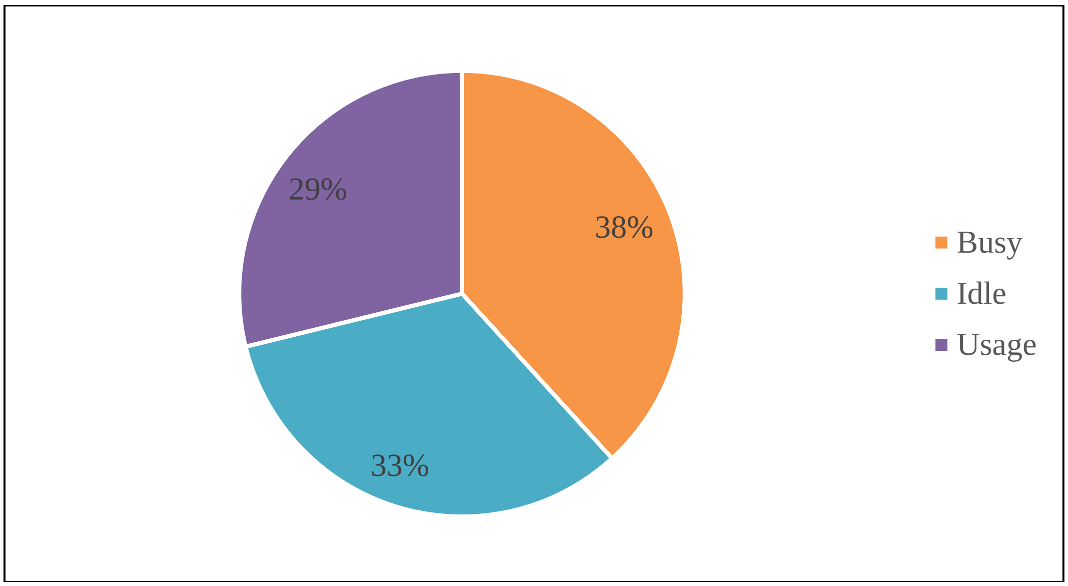


Figure 11: Ideal Case Resource Cost Breakdown

Base Case

Assuming that there is only a one 9-hour shift from Monday through Friday with a one hour lunch in between, 80 kits per arrival, and all other values set to their base value to represent the system as it currently operates the system can better utilize the operators. However, the number of completed RTGs drops to 459 ± 3 RTGs with an average total time of 2616 ± 77 hours, which significantly higher than the time spent in the system when operators are working 24/7. Having only one shift drives the resource cost down to $657,844, and the operators spend less time in an idle state waiting for work as seen in Figure 12.

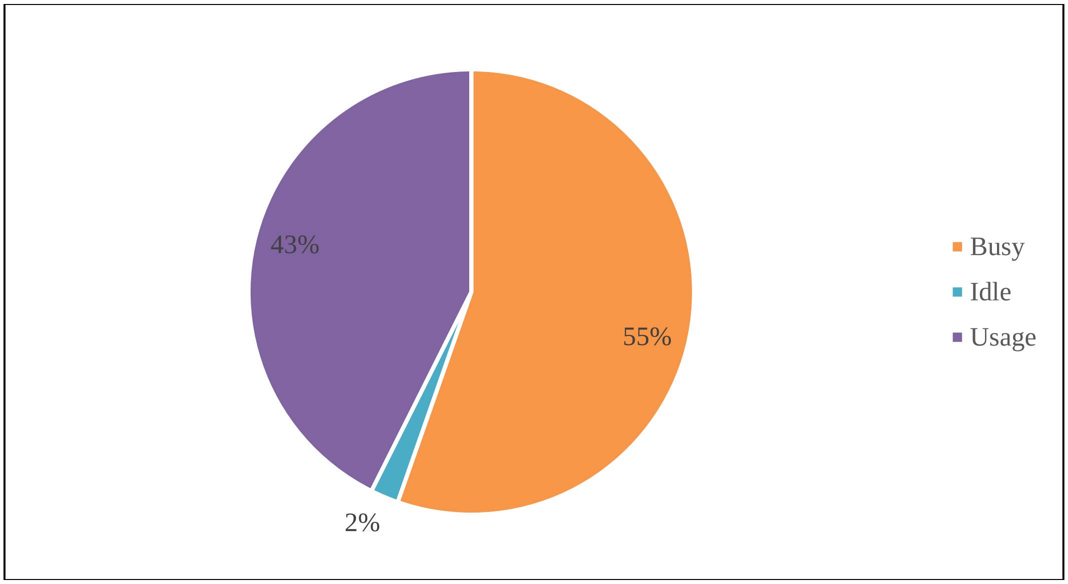


Figure 12: Base Case Resource Cost Breakdown at Base Values

The cost decreased, and resource utilization increased, however, the number of RTGs also went down with a more extended total time in the system. This extended time is not ideal as LANL wants to ensure that RTGs are produced as quickly as possible. Optimizing the system with the formulation given in the methodology in which all the objectives are weighted equally (Total Cost, Total Time, and Number Out) the system can produce RTGs more efficiently.

Optimized Base Case

Through the Scatter Search, the optimization yielded the values shown in Table 8 as the optimal set of variables that optimize the objective function.

Variable	**Units**	**Base Value**	**Optimal Value**
assemblyBatch	Kits	4	5
electricalBatch	RTGs	4	4
Line A	Kits	3	3
Line B	Kits	3	3
numTech	People	6	10
shockBatch	RTGs	2	2
vibrationBatch	RTGs	4	3
xenonBatch	RTGs	12	10

Table 8: Optimized Variable Values for Base Case

The most significant departure from the base case values is the number of operators which increases from six operators to ten. This is probably since at six operators the utilization of them is high, and there are products often waiting for an operator, and by adding extra operators, the usage goes down allowing for parts to wait less for an operator. The operator utilization before and after the optimization is seen in Figure 13.

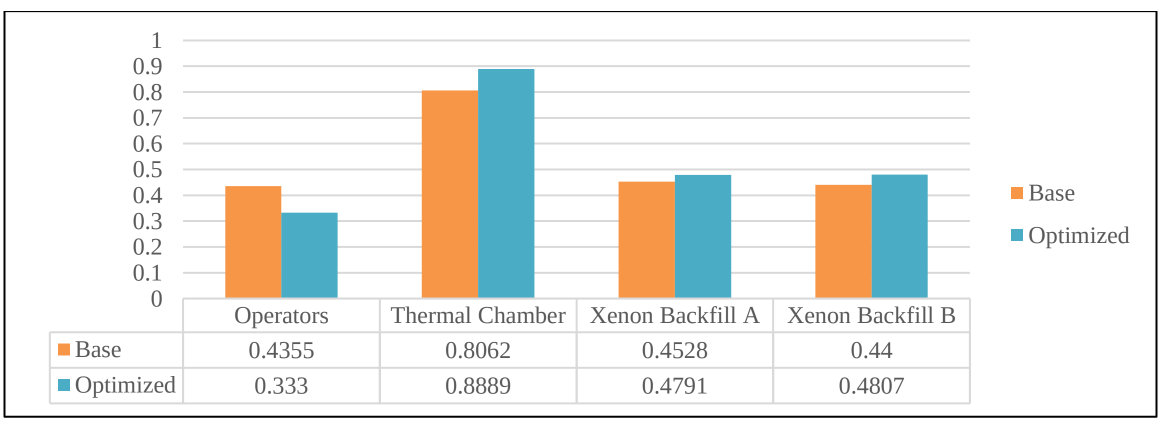


Figure 13: Base Case Resource Utilization Before and After Optimization

Other interesting utilization changes occurred for the thermal chambers and the xenon backfill chamber. In the optimal case, the utilization of these three resources went up. For the thermal chamber, the usage is already high ~80%, but in the optimal case, it is pushed up to ~90% utilization to push products out quicker. Having such high utilization makes this resource critical in such a way that if it goes down the entire process can bottleneck at this stage.

Using the optimal values from Table 8, the system can produce 520 ± 4 RTGs with an average total time of 2167 ± 85 hours. This results in a time savings of ~450 hours for each kit and an increase of ~60 RTGs. However, this optimum increases the total resource cost to $879,758 an increase of ~$220,000. This increase in price is mainly attributed to hiring four more operators.

Objective Function Sensitivity Analysis for Base Case

The objective function was varied by changing the value of w_3 which is associated directly with the reward function and the number of completed RTGs. Furthermore, the target number of RTGs for the reward function was increased to 600 RTGs to stress the system as it is less likely to meet this higher target than the previous target of 200 RTGs per year set by LANL. The results of this can be observed in Figure 14. At the extreme points, w_3 is chosen to be zero when the number of RTGs produced does not matter and one when this is the only thing LANL cares about in their decisions. The other two weights are chosen such that $w_1 + w_2 + w_3 = 1$ and that $w_1 = w_2$. When w_3 is chosen to be close to these extreme values, the number of completed RTGs remains approximately the same. This makes sense since for example w_3 is chosen to be 0.75, w_3 is still dominating the other two objectives and the objective system will essentially choose to optimize on the number of completed RTGs produced. The same is true for the case when w_3 is small, except for the other two objectives dominating the objective function.

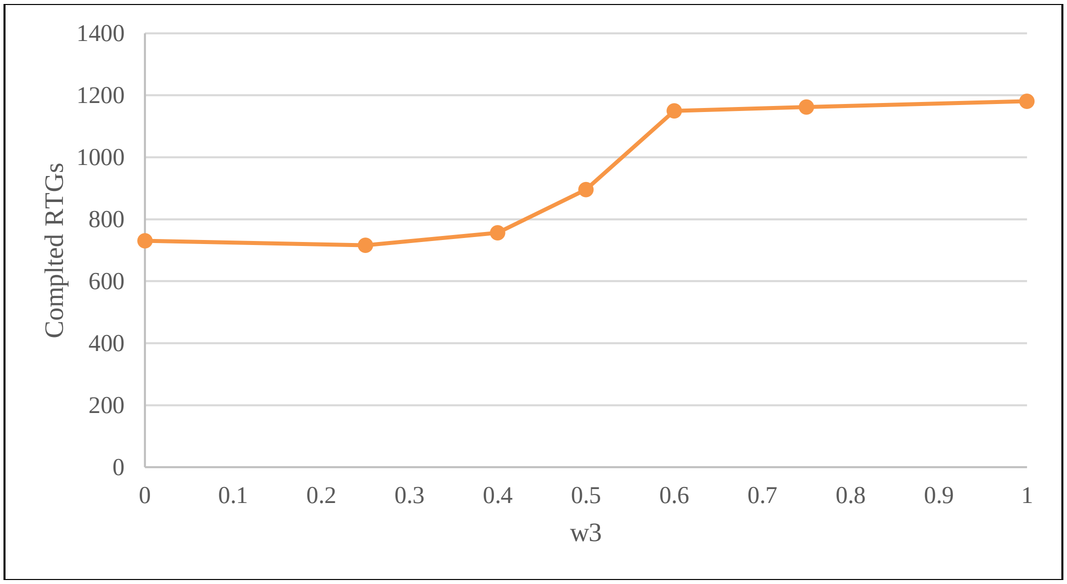


Figure 14: Sensitivity to Variation on w_3 for Objective Function in Base Case

Total Cost

The costs presented so far only include the cost of the operator's labor whether they are idle or busy and the cost of operating the xenon backfill chambers. However, there are other costs associated with the process to keep production going; these were presented in the methodology section. These costs are shown and broken-down by category in Figure 15. The total cost for an RTG is calculated to be $6,300 at the optimum base case with a total cost of ~$3,260,000 for all 520 RTGs produced in one typical year. It should be noted that the total cost does not include the value of the heat sources, as this cost is incurred in another process. Analyzing Figure 15 the most considerable cost arises from operating supplies with the bulk of this cost being the cost of running the xenon backfill chamber. This makes sense as the price of xenon is high, and it is incurred every time the xenon backfill machine is utilized. The second largest expense is payroll overhead, it is expected for this cost to be high as there are more employees than just the operators that must be accounted for in the total cost. This full cost analysis is only presented for the base case as it can easily be obtained for the other cases by scaling by the labor costs for each of the scenarios.

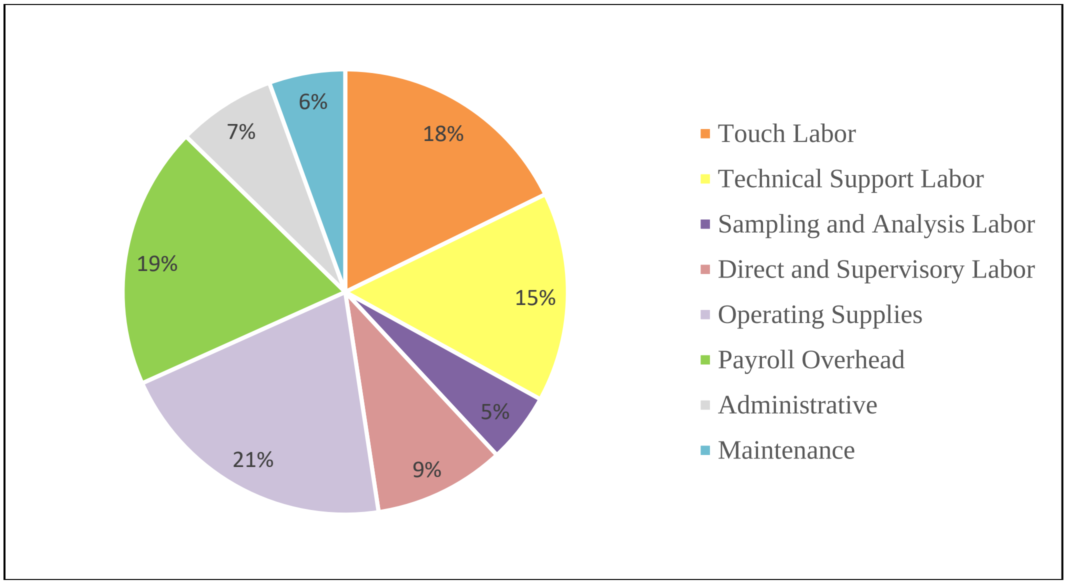


Figure 15: Total Cost Breakdown for Base Case

1.5 Shift Case

In this model, it was assumed that the operators come to work an extra five hours on Saturday morning to keep the products moving along. In this case, the system can produce 518 ± 5 RTGs with an average total time of 2349 ± 84 hours at a total resource cost of $739,281. Compared to the ideal case, this case reduces costs significantly with a reduction of RTG output and an increase in average total time in the system as seen in Figure 16.

Figure 16: Output Metric Comparison Between 1.5 Shifts and Ideal Scenarios

Optimized 1.5 Shifts Case

Through the Scatter Search, the optimization yielded the values shown in Table 9 as the optimal set of variables that optimize the objective function

Variable	Units	Base Value	Optimal Value
assemblyBatch	Kits	4	5
electricalBatch	RTGs	4	4
Line A	Kits	3	4
Line B	Kits	3	2
numTech	People	6	8
shockBatch	RTGs	2	2
vibrationBatch	RTGs	4	4
xenonBatch	RTGs	12	10

Table 9: Optimized Variable Values for 1.5 Shifts Case

As in the base case optimization, the system chooses to add more operators. However, in this case, it only adds two operators rather than four. This makes sense since you have extra time to work on the weekend you do not need as many operators overall as you can distribute the work across more working hours. In this optimized case the system can produce 595 ± 6 RTGs with an average total time of 1820 ± 75 hours. This represents an increase of ~80 extra RTGs and ~500 hours saved per kit. However, this comes at the expense of adding two extra workers and having all operators work an additional five hours to a total resource cost of $846,135 which represents an increase of ~$100,000.

TWO SHIFTS CASE

In this model, it is assumed that there is an entire separate crew that works at night to keep moving products along. The first and second team have two hours in between shifts, and each has an hour lunch, which signifies an 18-hour workday with 6 hours without operators. In this case, the system can produce 663 ± 7 RTGs with an average total time of 1708 ± 74 hours at a total resource cost of $1,080,844. Compared to the ideal case, this case minimally reduces the cost with a slight reduction of RTG output and an increase in average total time in the system as seen in Figure 17. This is not very different from the ideal case when comparing the output metrics.

Figure 17: Output Metric Comparison Between Two Shifts and Ideal Scenarios

Optimized Two Shifts Case

Through the Scatter Search, the optimization yielded the values shown in Table 10 as the optimal set of variables that optimize the objective function.

Variable	Units	Base Value	Optimal Value
assemblyBatch	Kits	4	4
electricalBatch	RTGs	4	4
Line A	Kits	3	3
Line B	Kits	3	3
numTech	People	6	6
numTech2	People	6	8
shockBatch	RTGs	2	2
vibrationBatch	RTGs	4	3
xenonBatch	RTGs	12	11

Table 10: Optimized Variable Values for Two Shifts Case

In the optimal configuration, the system chooses to add more operators to the second shift. It decides to add two more operators which intuitively makes sense since the products from the first shift are ready to be moved in the second shift and the second shift still needs to process products from the second shift. Adding the two extra operators helps with having to remove the products from their finished test and on to the next. In this optimized case the system can produce 663 ± 8 RTGs with an average total time of 1553 ± 73 hours. In this case, the number of RTGs remains about the same which makes sense since the system is almost always running with operators present. There is a slight decrease in time of ~160 hours and an increase in price ~$100,000. The price increases due to having more operators on the second shift, which also helps reduce the total time slightly.

MACHINES FAIL CASE

In this case, it is assumed that there is no preventive maintenance done and that machines are repaired only when they fail. The mean time between failures can be modeled by an exponential distribution, one of the most common distributions used in reliability engineering [55] [56]. The probability density function of the exponential distribution is shown in Eq. 25. Where, λ is the failure rate and t is time.

$$f(t) = \lambda e^{-\lambda t} \qquad \text{Eq. 25}$$

Eq. 25 can be integrated to show that the cumulative distribution function is equal to $F(t)$ as shown in Eq. 26.

$$F(t) = 1 - e^{-\lambda t} \qquad \text{Eq. 26}$$

This formulation states that as time progresses the probability of encountering a failure increases. Such that at the initial time, $t = 0$, the probability of failure is $F(t) = 0$. However, in the other extreme when, $t = \infty$, the probability of failure is $F(t) = 1$. This intuitively makes sense, that as time progresses the machine is more likely to breakdown as wear increases.

Figure 18 shows the number of completed RTGs as a function of the mean time between failures. It is seen that at 50 or more days the number of completed RTGs reaches an asymptote of approximately 500 RTGs. However, if the mean time between arrivals is less than 50 days, the number of completed RTGs starts to drop off significantly. For analysis, 12 days between failures is chosen as the base case in which failures occur in each of the different machines.

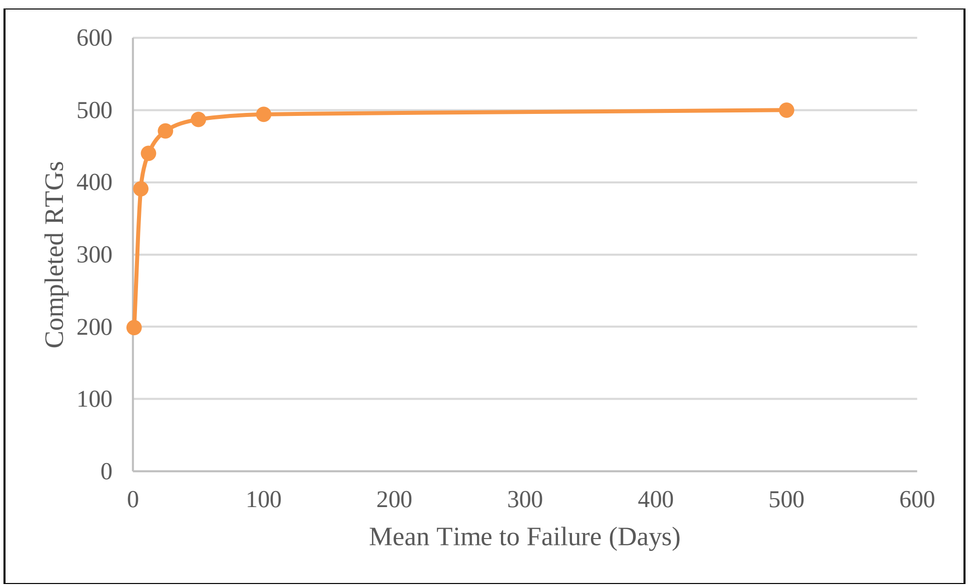


Figure 18: Sensitivity on Mean Time to Failure

In this case, the system can produce 440 ± 4 RTGs with an average total time of 2598 ± 85 hours at a total resource cost of $804,696. Compared to the ideal case, this case reduces the cost with a reduction of RTG output and a significant increase in the average total time in the system as seen in Figure 19. Furthermore, for this case when machines break, there is also a cost associated with having operators wait for machines to come back online. At base values with the machines failing with a mean time of 12 days, the waiting cost amounts to ~$20,000 or 4% of the total operating cost. This incurred cost could have been invested in maintenance, which would have ultimately increased the production rate.

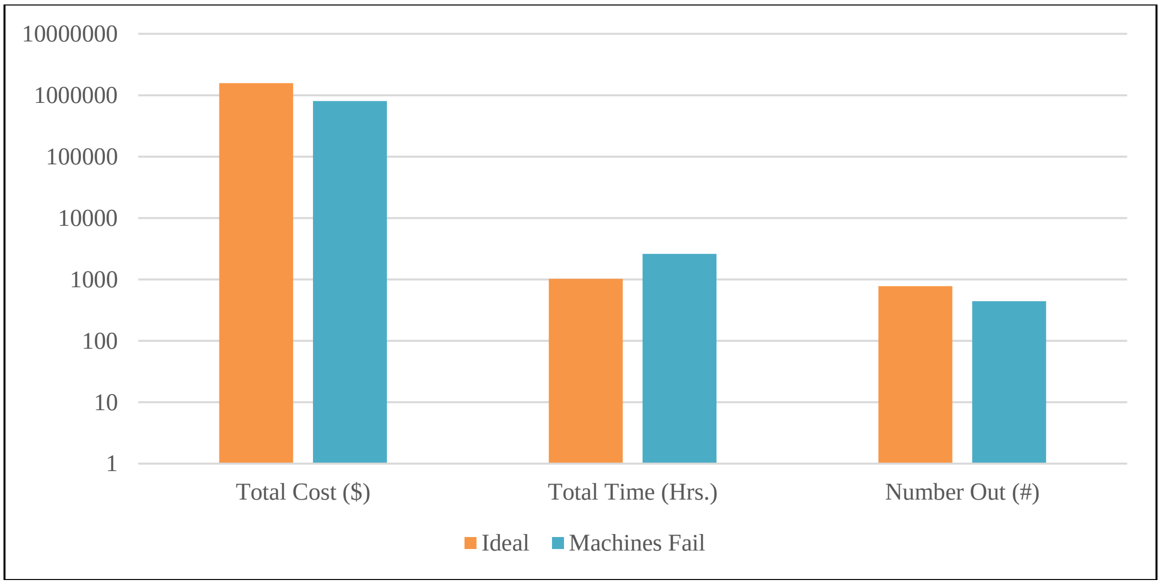


Figure 19: Output Metric Comparison Between Machines Fail and Ideal Scenarios

Optimized Machines Fail Case

Through the Scatter Search, the optimization yielded the values shown in Table 11 as the optimal set of variables that optimize the objective function.

Variable	Units	Base Value	Optimal Value
assemblyBatch	Kits	4	4
electricalBatch	RTGs	4	4
Line A	Kits	3	4
Line B	Kits	3	5
numTech	People	6	9
shockBatch	RTGs	2	2
vibrationBatch	RTGs	4	4
xenonBatch	RTGs	12	8

Table 11: Optimized Variable Values for Machines Fail Shifts Case

In the optimal configuration, the system decides to increase the number of operators from six to nine. Adding the three new operators helps the system move the products more efficiently, especially when a broken machine stalls the products. The second largest change is the system decides to decrease the xenon batch size from 12 to eight RTGs. It is interesting that the system chooses to reduce the total time per product by incurring more usage costs of the xenon backfill chamber by running smaller batches. In the optimal configuration, the system can produce 458 ± 3 RTGs, which is a slight increase in output. This modest increase can be attributed to the significant wait times the RTGs experience already due to the machine failures. Furthermore, the RTGs spend 2555 ± 82 hours in the system, which is no significant decrease in total time.

Comparison of All Cases at Optimal Values

In this section, the results for all the different cases are compared to each other by normalizing all values by the values obtained from the ideal case.

Total Cost

It can be seen in Figure 20, that the normalized cost is minimized when utilizing the 1.5 shifts policy and the most expensive policy is the two-shift strategy. It makes sense that the two-shift plan is the most costly as the system is having operators work for most of the day and they are not being utilized. However, the 1.5 shifts being the lowest cost is interesting since in the optimal configuration it is more cost efficient than the base case with only one shift. This can be attributed to running larger batches and avoiding having to pay more usage fees for the xenon backfill step.

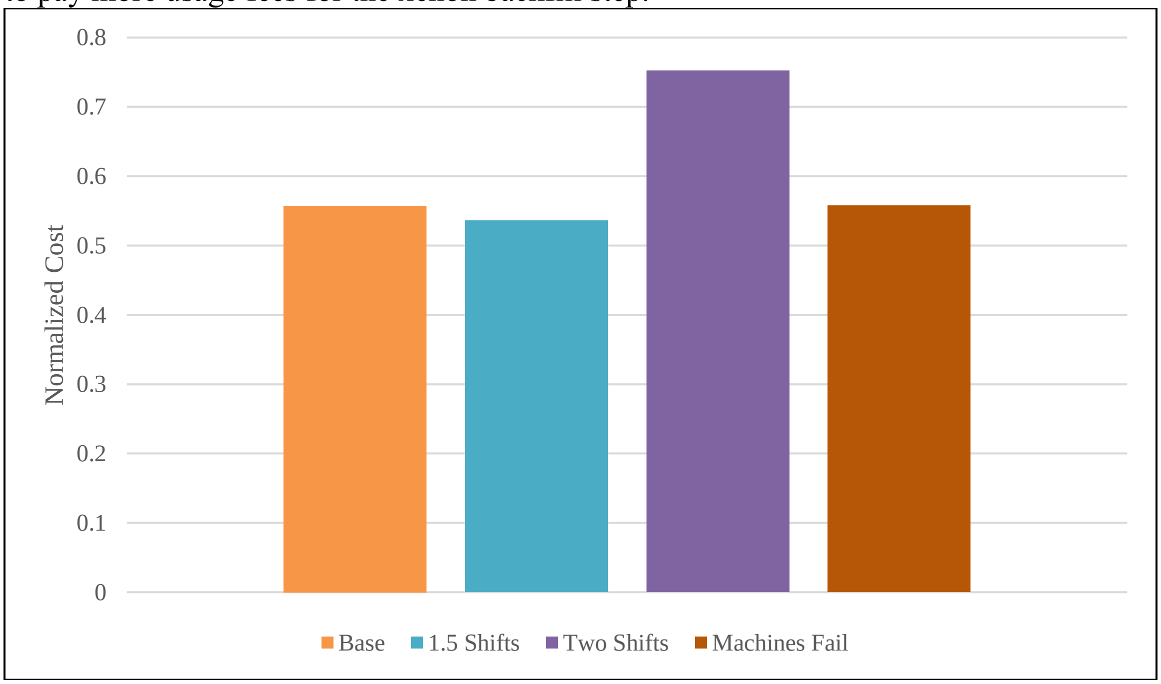


Figure 20: Comparison of Total Cost for Different Policies

Total Time

The normalized total time per RTG is seen in Figure 21, where the strategy of letting machines fail forces the system to keep the RTGs in the system for a more extended period in which the machines are repaired. On the other hand, having two shifts minimizes the time RTGs spend in the system. This makes sense as there will be an operator available most of the time to keep the product moving, and there is little to no lag time. This lag time is evident with the base one shift, and the 1.5 shifts as the RTGs must wait for most of the weekend to be moved to their next step. Having the extra half working day on Saturday allows the 1.5 shifts to outperform the one shift base strategy significantly.

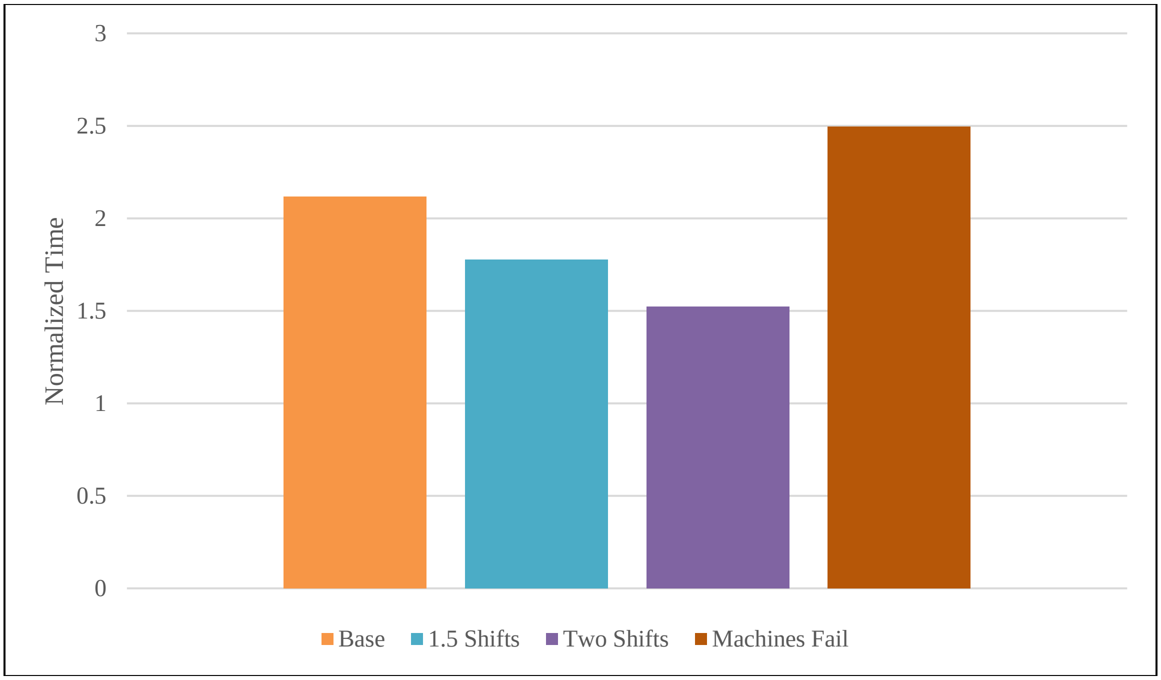


Figure 21: Comparison of Total Time for Different Policies

RTGs Completed

The normalized number of RTGs completed is shown in Figure 22. It is evident that the two-shift policy allows for the system to maximize the throughput, for the same reason as it minimizes the time: operators are almost always available to move the product on to the next step. However, the increase is not substantial compared to the 1.5 shifts strategy; it only adds about 9% more completed RTGs. The worse performing policy is to allow the machines to fail which significantly decreases the output of the system by keeping the RTGs for a longer time.

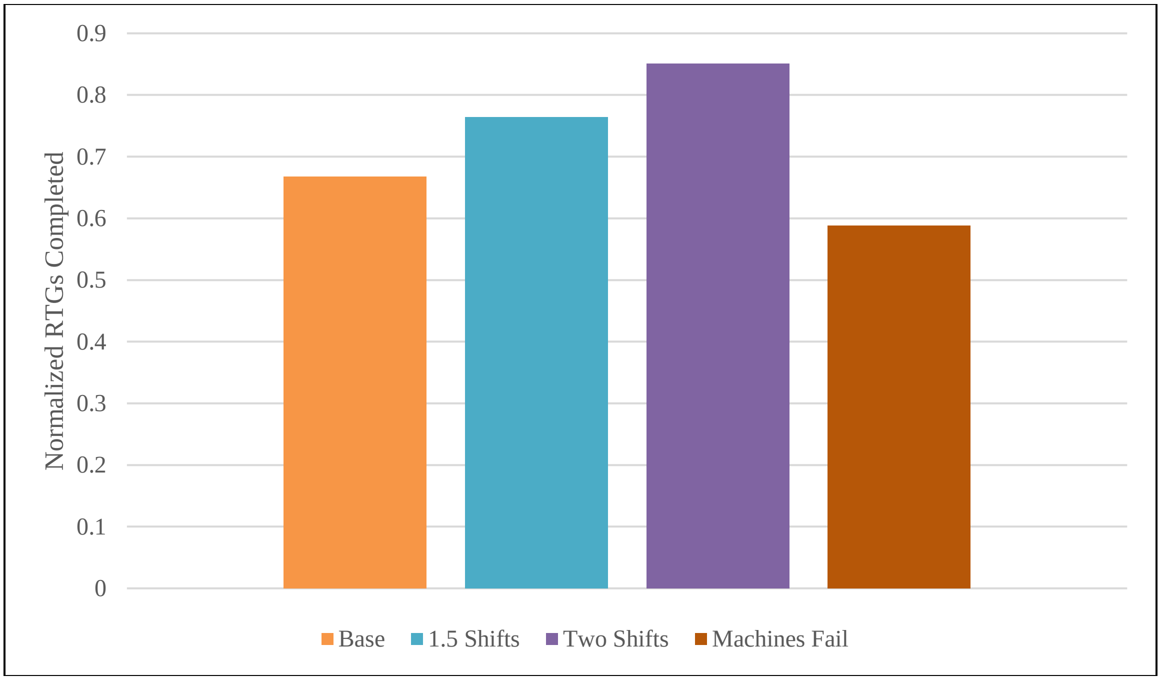


Figure 22: Comparison of RTGs Completed for Different Policies

Conclusion

This thesis presented the successful optimization of different policies that LANL can pursue to meet their RTG production targets. First, the system under review was described. Second, deterministic and stochastic cost modeling methodologies were presented to capture the dynamic nature of the system. Third, the parameter space and constraints of the system were explored to show how the system can change. Last, the different policies were optimized for eight decision variables in a multi-objective problem.

Contingent on LANL's priorities, one or more cases can be attractive to decrease time spent in the system while increasing the number of completed RTGs. This was shown by the "ideal" strategy in which operators work around the clock and the two-shift policy. These two mainly optimized these conditions but neglected to consider the cost of having operators almost or all day. Furthermore, the utilization of operators is low with these two scenarios, in which the operators spend most of their time in an idle state waiting for work.

On the contrary, it was shown that there are also policies that should never be implemented like allowing for machines to fail and then repair them. This plan had the worst performance in the time spent in the system, and the number of RTGs completed. Furthermore, with this strategy, there was a cost incurred of having to wait for the failed machine to be replaced. It would be of interest to LANL to invest this money in preventative maintenance rather than repairing the machines when they are broken.

Finally, it is shown that the best policy for LANL to pursue is adding an extra shift on Saturdays to maximize the number of RTGs out and the resource utilization while minimizing the total system cost. This strategy hedges the time lost during the weekend by adding a shift where parts are transitioned to the next step. Adding this extra half-working day increases the total minimally while making substantial savings in the total time spent in the system and producing more RTGs overall. With this strategy, the cost per RTG is valued at $6,000 with a yearly manufacturing cost of $3M.

It is of interest to LANL to explore more scenarios and strategies which add more complexity to the system to help drive decisions about day to day activities to meet manufacturing targets. In the future, the following cases should be studied to further quantify the system under different conditions:

- Adding learning curves into the time, it takes operators to conduct procedures. The RTG manufacturing process is new to LANL, but it is expected that with time, the time for different steps of the process should decrease as the operators become more familiar with the machines and steps. It is of interest to find out what is the theoretical max of number of RTGs produced that the system can reach as the operators become "experts" in the process
- A shortfall of the current model is the need to assume the arrivals of heat sources from PF-4 to PF-5. Once there is historical data on this, the model should incorporate this to make it more realistic. Furthermore, it was of interest to LANL to model the different products manufactured in PF-4 and directly couple this model to the RTG model. In this secondary model, the intricate dynamics of PF-4 with its many different product lines drive the demand in PF-5.
- Allowing the system to optimize over more decision variables. Currently, the model assumes that space is limited and therefore no more machines can be added. However, it is of interest what to know what type of extra capacity should be built to maximize LANL's objectives and what the benefits of this additional capacity signify to overall operations.
- Having multiple product lines for variants of the RTG. It is of interest to see how changeover time from one product line to another affects the number of completed

products. Furthermore, what is the optimal way to utilize the current two lines? Should different product lines work in parallel, or should a line work on a product and the second on another?

The results concluded in this thesis can help LANL make their current decisions with the new launch of the RTG manufacturing. As the production needs change over time, this methodology can be adapted to reflect that and optimize future systems. Furthermore, this methodology can be expanded to other product lines throughout LANL to help minimize costs by utilizing current resources as efficiently as possible.

Appendix A: Arena Model

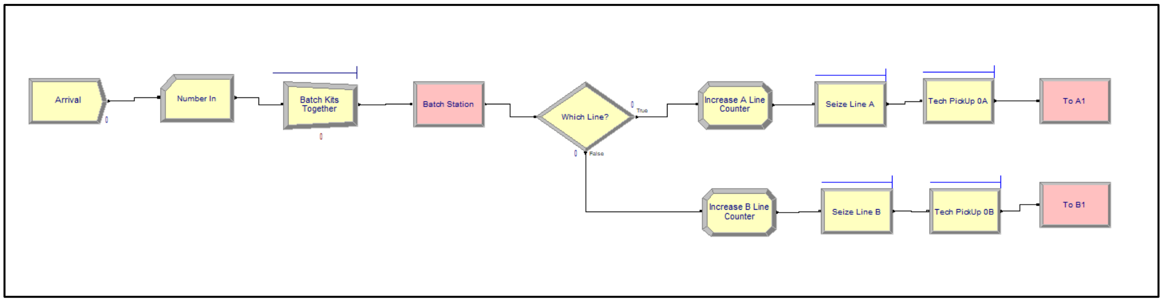


Figure 23: Arena Arrival Logic

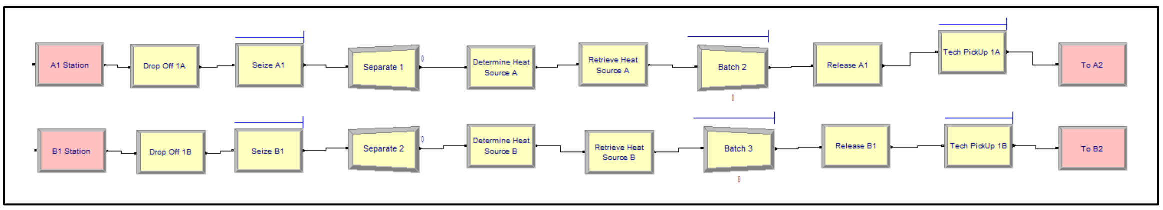


Figure 24: Arena Box 1 Logic

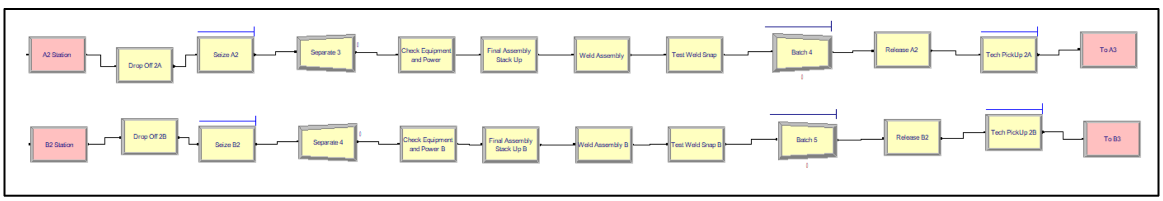


Figure 25: Arena Box 2 Logic

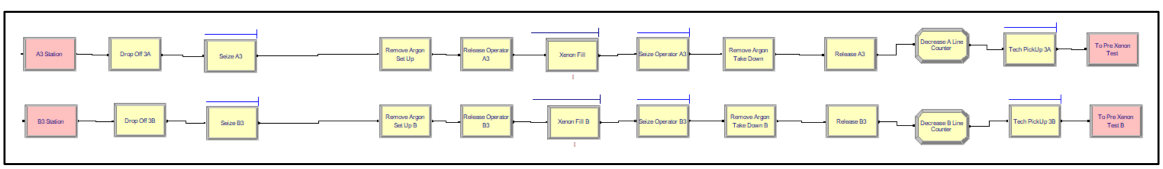


Figure 26: Arena Box 3 Logic

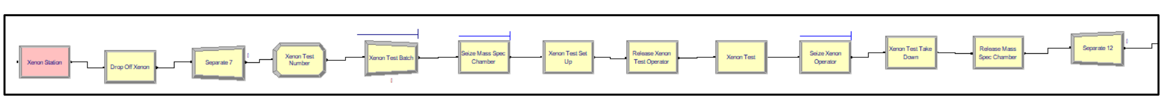


Figure 27: Arena Xenon Test Logic Part 1

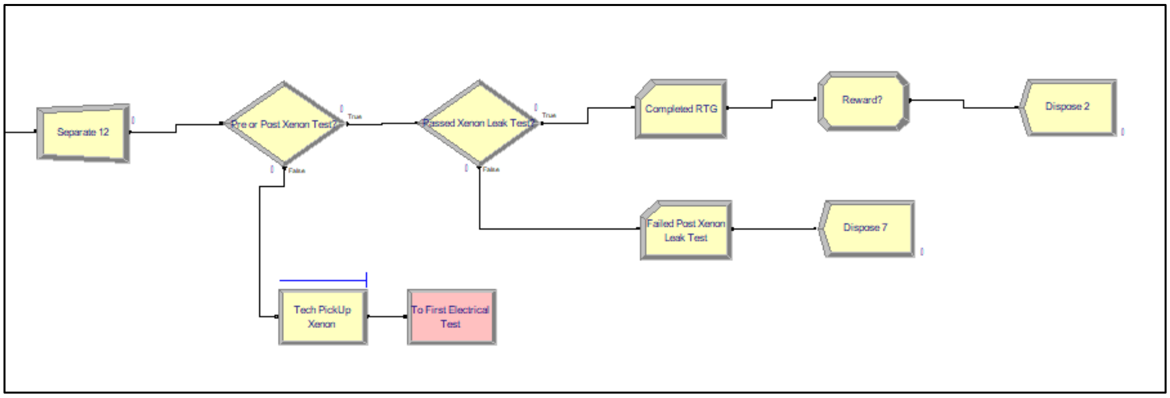


Figure 28: Arena Xenon Test Logic Part 2

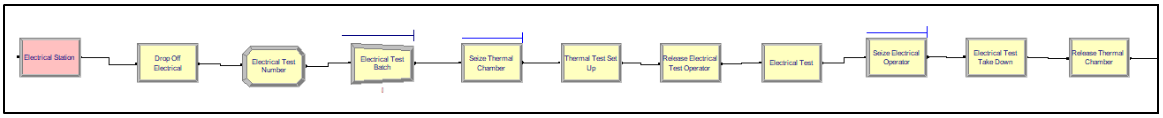


Figure 29: Arena Electrical Test Logic Part 1

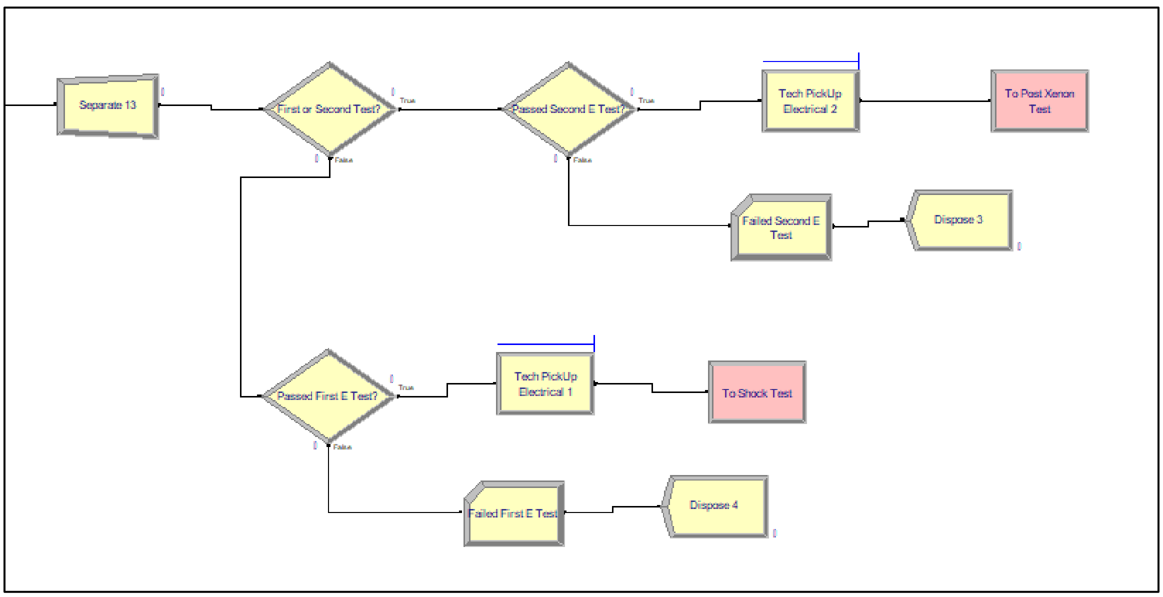


Figure 30: Arena Electrical Test Part 2

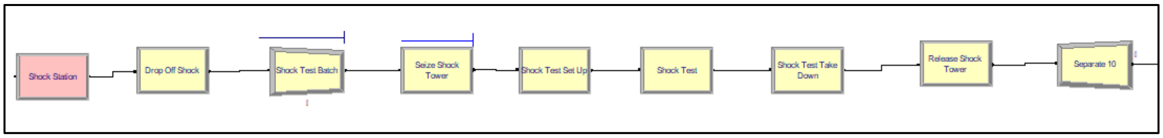


Figure 31: Arena Shock Test Logic Part 1

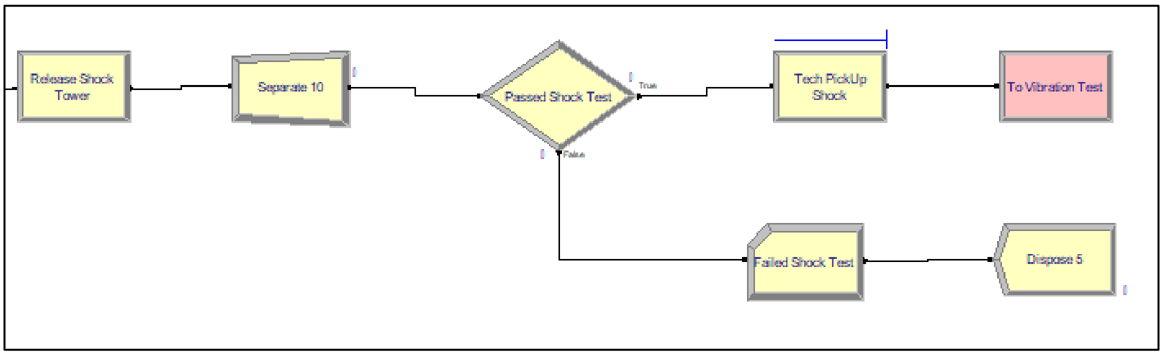


Figure 32: Arena Shock Test Logic Part 2

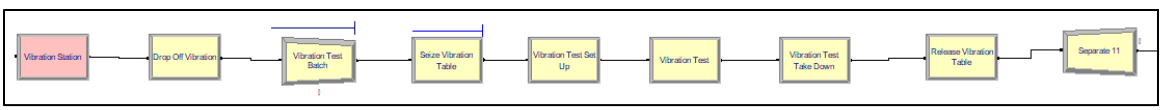


Figure 33: Arena Vibration Logic Part 1

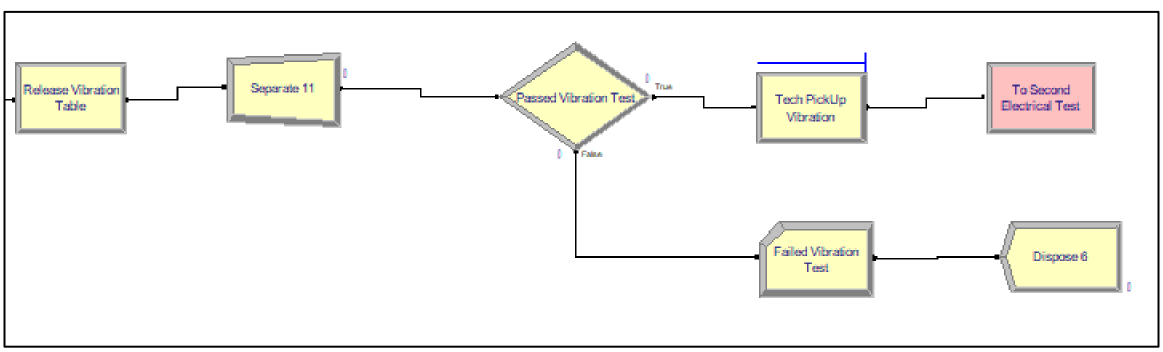


Figure 34: Arena Vibration Logic Part 2

Appendix B: Arena Sample Output File

ARENA Simulation Results
jparga_23@utexas.edu - License: 2959005749

Summary for Replication 1 of 3

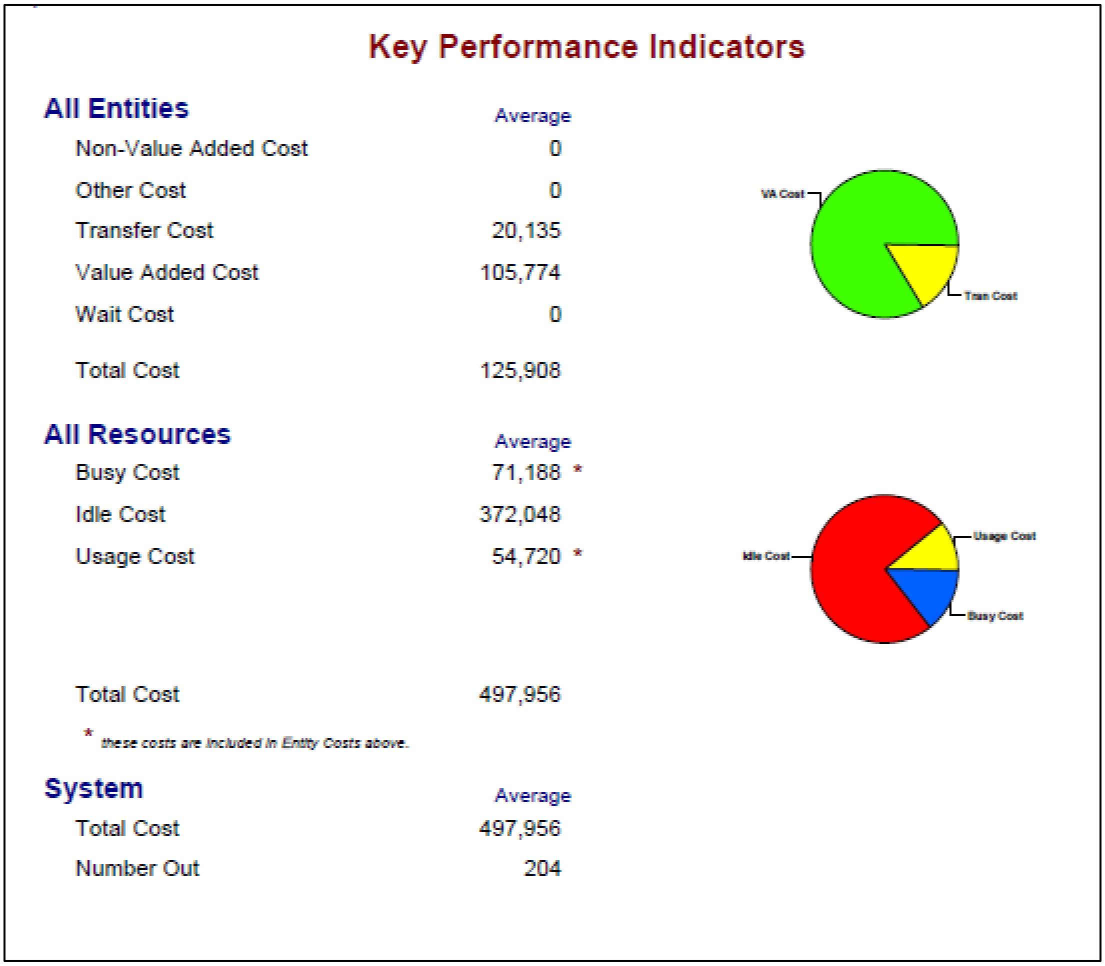
Project: RTG Manufacturing — Run execution date :12/ 5/2017
Analyst: Jose Parga — Model revision date:12/ 5/2017

Replication ended at time : 8760.0 Hours
Base Time Units: Hours

TALLY VARIABLES

Identifier	Average	Half Width	Minimum	Maximum	Observations
Kits.VATime	157.28	7.1564	90.822	204.12	324
Kits.NVATime	.00000	.00000	.00000	.00000	324
Kits.WaitTime	4082.0	(Corr)	230.04	8423.9	324
Kits.TranTime	6.2069	.29775	3.1414	8.1407	324
Kits.OtherTime	.00000	.00000	.00000	.00000	324
Kits.TotalTime	4245.4	(Corr)	354.41	8604.5	324
Kits.VACost	693.26	25.447	349.93	845.58	324
Kits.NVACost	.00000	.00000	.00000	.00000	324
Kits.WaitCost	.00000	.00000	.00000	.00000	324
Kits.TranCost	95.278	6.5032	30.597	134.23	324
Kits.OtherCost	.00000	.00000	.00000	.00000	324
Kits.TotalCost	788.54	31.630	384.73	970.86	324
Tech PickUp Vibration.Queue.WaitingTime	69.293	(Insuf)	21.134	128.13	218
Tech PickUp Vibration.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	218
Seize Line B.Queue.WaitingTime	3486.8	(Insuf)	.00000	8607.7	22
Seize Line B.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	22
Seize Line A.Queue.WaitingTime	3076.9	(Insuf)	.00000	5969.7	84
Seize Line A.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	84
Tech PickUp 1B.Queue.WaitingTime	57.188	(Insuf)	.00000	98.419	21
Tech PickUp 1B.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	21
Tech PickUp 1A.Queue.WaitingTime	54.080	(Insuf)	.00000	125.19	82
Tech PickUp 1A.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	82
Seize Electrical Operator.Queue.WaitingTim	70.053	(Insuf)	4.1429	131.51	280
Seize Electrical Operator.Queue.WaitingCos	.00000	(Insuf)	.00000	.00000	280
Batch 2.Queue.WaitingTime	.06897	.00714	.00000	.42120	332
Batch 2.Queue.WaitingCost	.00000	.00000	.00000	.00000	332
Seize Thermal Chamber.Queue.WaitingTime	216.05	(Insuf)	2.2045	473.47	284
Seize Thermal Chamber.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	284
Seize B3.Queue.WaitingTime	57.678	(Insuf)	.00000	115.11	21
Seize B3.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	21
Seize B2.Queue.WaitingTime	43.485	(Insuf)	.00000	111.26	21
Seize B2.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	21
Seize B1.Queue.WaitingTime	48.091	(Insuf)	.00000	128.10	21
Seize B1.Queue.WaitingCost	.00000	(Insuf)	.00000	.00000	21

Figure 35: Arena Replication Sample Output



Key Performance Indicators

All Entities	Average
Non-Value Added Cost	0
Other Cost	0
Transfer Cost	20,135
Value Added Cost	105,774
Wait Cost	0
Total Cost	125,908

All Resources	Average
Busy Cost	71,188 *
Idle Cost	372,048
Usage Cost	54,720 *
Total Cost	497,956

* these costs are included in Entity Costs above.

System	Average
Total Cost	497,956
Number Out	204

Figure 36: Key Performance Indicators Arena Sample Output

Time

VA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Kits	156.45	0.60	149.93	163.09	84.4031	212.60

NVA Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Kits	0.00	0.00	0.00	0.00	0.00	0.00

Wait Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Kits	481.59	17.00	301.80	821.38	10.9412	3923.37

Transfer Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Kits	6.1516	0.02	5.8568	6.4561	2.9615	8.4446

Other Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Kits	0.00	0.00	0.00	0.00	0.00	0.00

Total Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Kits	644.19	16.91	463.90	979.22	118.32	4124.94

Figure 37: Entity Time Statistics Arena Sample Output

Time

Waiting Time	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Batch 2.Queue	0.07250928	0.00	0.05334075	0.0900	0.00	0.3921
Batch 3.Queue	0.07299531	0.00	0.06099565	0.0925	0.00	0.4210
Batch 4.Queue	0.1032	0.00	0.08087434	0.1280	0.00	0.5901
Batch 5.Queue	0.1017	0.00	0.08159987	0.1243	0.00	0.5756
Batch Kits Together.Queue	0.00	0.00	0.00	0.00	0.00	0.00
Electrical Test Batch.Queue	39.8580	2.32	13.7751	91.6170	0.00	2782.12
Seize A1.Queue	0.6977	0.10	0.1489	2.5250	0.00	15.0637
Seize A2.Queue	0.7975	0.08	0.1431	1.9705	0.00	15.0101
Seize A3.Queue	14.1011	0.81	2.6731	23.5034	0.00	93.0205
Seize B1.Queue	0.7282	0.12	0.1056	2.5315	0.00	15.8532
Seize B2.Queue	0.7614	0.09	0.08248543	2.9681	0.00	16.7229
Seize B3.Queue	15.1956	0.99	5.3229	28.0685	0.00	93.6134
Seize Electrical Operator.Queue	6.7801	0.11	5.2639	7.9500	0.00	14.9542
Seize Line A.Queue	0.4780	0.26	0.00	8.0273	0.00	111.21
Seize Line B.Queue	0.6719	0.26	0.00	7.2012	0.00	70.1587
Seize Mass Spec Chamber.Queue	0.8249	0.11	0.06741959	2.5667	0.00	14.2793
Seize Operator A3.Queue	6.5847	0.21	3.6475	9.6951	0.00	15.5070
Seize Operator B3.Queue	6.6286	0.23	4.1067	9.1753	0.00	16.2315
Seize Shock Tower.Queue	9.1266	0.35	5.3353	17.0023	0.00	67.8489
Seize Thermal Chamber.Queue	3.3228	0.17	0.7784	5.2131	0.00	48.6991
Seize Vibration Table.Queue	0.5217	0.07	0.00433406	1.4549	0.00	19.9994
Seize Xenon Operator.Queue	1.3654	0.16	0.00	2.9266	0.00	14.7240
Shock Test Batch.Queue	24.6322	1.60	7.4565	55.9279	0.00	2901.85
Tech PickUp 0A.Queue	3.9426	0.23	1.6333	6.9645	0.00	14.7422
Tech PickUp 0B.Queue	4.0973	0.20	1.6274	6.9210	0.00	14.5427
Tech PickUp 1A.Queue	0.6292	0.12	0.00	2.9705	0.00	14.1649
Tech PickUp 1B.Queue	0.6373	0.10	0.00	1.9868	0.00	16.1221
Tech PickUp 2A.Queue	1.5213	0.15	0.3208	3.4551	0.00	15.6300
Tech PickUp 2B.Queue	1.4961	0.14	0.3667	3.2954	0.00	16.4641
Tech PickUp 3A.Queue	0.9468	0.12	0.00	2.9959	0.00	15.9051
Tech PickUp 3B.Queue	0.9368	0.13	0.00	3.0144	0.00	15.7617
Tech PickUp Electrical 1.Queue	0.6257	0.06	0.1216	1.5606	0.00	15.6122
Tech PickUp Electrical 2.Queue	0.5973	0.09	0.00320359	1.7683	0.00	15.6436
Tech PickUp Shock.Queue	7.0866	0.12	4.9297	8.4121	0.00	17.3708
Tech PickUp Vibration.Queue	1.3763	0.14	0.2371	3.5903	0.00	16.6026
Tech PickUp Xenon.Queue	2.0102	0.18	0.3780	5.1820	0.00	17.0093

Figure 38: Queue Time Statistics Arena Sample Output

Usage

Instantaneous Utilization	Average	Half Width	Minimum Average	Maximum Average	Minimum Value	Maximum Value
Box A1	0.00333887	0.00	0.00158076	0.00543131	0.00	1.0000
Box A2	0.00654430	0.00	0.00312067	0.01052110	0.00	1.0000
Box A3	0.1342	0.01	0.06334083	0.2111	0.00	1.0000
Box B1	0.00337108	0.00	0.00147057	0.00538805	0.00	1.0000
Box B2	0.00660332	0.00	0.00287722	0.01054847	0.00	1.0000
Box B3	0.1349	0.01	0.05674985	0.2202	0.00	1.0000
Line A	0.07248024	0.00	0.02937718	0.1169	0.00	1.0000
Line B	0.07428791	0.00	0.02973449	0.1267	0.00	1.0000
Mass Spec	0.00867394	0.00	0.00411140	0.01388671	0.00	0.1667
Shock Tower	0.07873882	0.00	0.03790368	0.1132	0.00	1.0000
Technician	0.0977	0.00	0.04716305	0.1520	0.00	1.0000
Thermal Chamber	0.1225	0.00	0.06314112	0.1923	0.00	1.0000
Vibration Table	0.04612600	0.00	0.02298798	0.06965680	0.00	1.0000
Xenon Backfill Chamber	0.08701178	0.00	0.04031077	0.1396	0.00	1.0000
Xenon Backfill Chamber B	0.08739694	0.00	0.03752396	0.1390	0.00	1.0000

Figure 39: Utilization Statistics Arena Sample Output

Count	Average	Half Width	Minimum Average	Maximum Average
FailETest1	32.0200	1.44	16.0000	54.0000
FailETest2	19.3100	1.12	3.0000	35.0000
FailShockTest	27.1300	1.31	11.0000	44.0000
FailVibrationTest	22.4400	1.26	8.0000	39.0000
FailXenonTest	15.0900	0.88	5.0000	27.0000
FinishedRTG	87.9500	3.96	37.0000	149.00
numIn	219.36	7.64	120.00	328.00

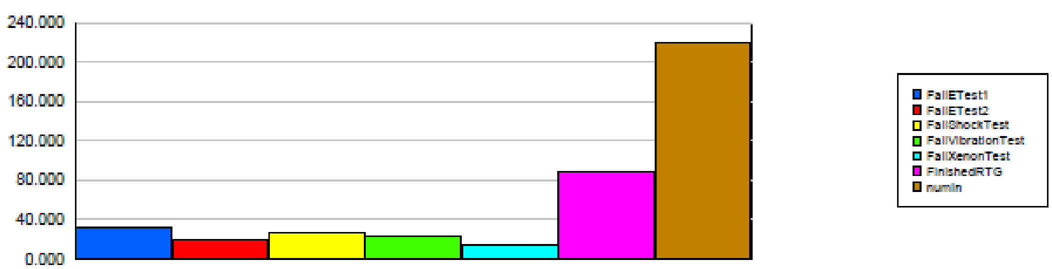


Figure 40: User Defined Variable Statistics Arena Sample Output

Glossary

DOE – Department of Energy

LANL – Los Alamos National Laboratory

MES - Manufacturing Execution System

MMRTG – Multi Mission Radioisotope Thermal Generator

MRP - Material Requirement Planning

NASA -National Aeronautics and Space Administration

PF-4 – Plutonium Facility 4

PF-5 – Plutonium Facility 5

PFD – Process Flow Diagram

QA – Quality Assurance

RTG – Radioisotope Thermal Generator

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Vita

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